Hidde Hessel Hereijgers

MSc Student Forest and Nature Conservation

Wageningen University and Research

Pedunculate Oak Decline

Quercus robur L.

Unraveling Growth Declines and Climatic Influences in Pedunculate Oak Through:

Dendrochronology

Veluwe Area The Netherlands

First edition

Published Wageningen Universiteit, 10 March 2025, AV2025-08

Supervisors: dr.ir. Paul Copini & dr. Ute Sass-Klaassen

Pedunculate Oak Decline in the Netherlands

Unravelling Growth Declines and Climatic Influences in Pedunculate Oak Through Dendrochronological Research

Hidde H. Hereijgers (1297511)
Thesis FEM80436
AV2025-08
10-03-2025

Supervisor: dr.ir. Paul Copini (Forest Ecology Management chair group)
Second examiner: dr. Ute Sass-Klaassen (WUR/HVHL)

Wageningen University & Research, Wageningen

Source front page oak leaves: (IStock, 2025)

Contents

Abstract

Pedunculate oak (*Quercus robur*) is a key broadleaf tree species in northwestern Europe. The pedunculate oak is valued for its ecological and economic importance. However, oak decline has been an issue, with its mortality linked to various abiotic and biotic stressors, including drought, frost, pest infestations and nutrient imbalances. This study investigates long-term growth trajectories and climate-growth relationships of living and dead pedunculate oaks in two Dutch forest sites, Eikenheg and Heidenseberg, using dendrochronology. A total of 26 trees were cored (13 per site, including seven dead and six living trees), and we measured the annual growth rings to identify periods of growth decline and the influence of climate variables using climate data from the Bilt.

Results indicate that oak decline at Eikenheg began in the 1980s, with significant reductions in tree-ring width (TRW) following drought years (1983, 1984, and 1996) until mortality in 2001, 2005, 2006, 2007, 2008, 2010 and 2015. At Heidenseberg, tree decline was linked to a negative growth response after 1992, until mortality in 1994, 2008, 2009, 2012, 2013, 2016 and 2021. Climate-growth correlations revealed that living trees at Eikenheg benefited from warm May temperatures, while those at Heidenseberg responded positively to mild winter conditions. In contrast, dead trees exhibited a strong negative response to hot summers, particularly in July and August of the previous year, suggesting increased drought sensitivity. Additionally, negative pointer years coincided with severe winters (e.g., 1942, 1956, and 1963) and drought periods.

Soil analysis highlights the role of nutrient imbalances in oak decline, with severely acidified soils, low potassium and magnesium concentrations, and high aluminum levels contributing to reduced vitality. These findings suggest that oak mortality is driven by the cumulative effects of drought, cold stress, and poor soil conditions. The results support the hypothesis that dead trees exhibit greater sensitivity to climate extremes than living oaks. Further research into soil restoration strategies, such as rock dust applications, could help mitigate decline and improve tree resilience.

1.0 Introduction

1.1 Relevance of pedunculate oak

Pedunculate oak (*Quercus robur*) is one of the most important broadleaf tree species in northwestern Europe including the Netherlands (Eaton et al., 2015; Krutovsky et al., 2025; Oosterbaan, A. Bobbink, R. Decuyper, 2014). It has a large ecological amplitude (see figure 1) and the wood has a high commercial value (Thomas et al., 2002 & Eaton et al., 2015). Unfortunately, pedunculate oak has shown a decline in vitality, starting in the 1980ies (Oosterbaan & Nabuurs, 1991; Turok et al., 1997). According to Boer & Schils (2011) more than 400 insect species forage on pedunculate oaks (Boer & Schils, 2011; Krutovsky et al., 2025). Pedunculate oak occurs across a large part of central Europa (figure 1). It is a long lived tree species, can become up to a 1000 years old, and up to 40m tall, but usually becomes up to 30m tall and 1m in diameter (Eaton et al., 2015). Pedunculate oak prefers fertile and moist soils (Ellenberg, 1988). The wood of the pedunculate oak has been used for millennia, for buildings, furniture, ship construction and harvested in coppiced system, for firewood and for tannic acid used in leather processing. Therefore pedunculate oak has been planted abundantly throughout Europa (Heybroek, 1989; Eaton et al., 2015).

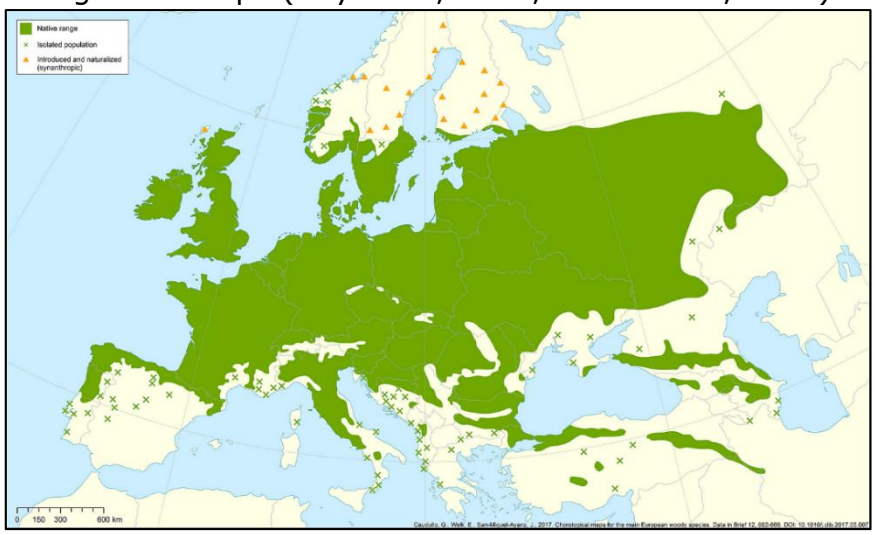

Figure 1: Map of pedunculate oak presence in Europa. Green represents the native range; green crosses represent isolated populations and orange triangles are introduced and naturalized populations Source: (Caudullo et al., 2017).

1.2 Oak decline in Europe

During the past century there has been multiple phases of dieback in Europe including the Netherlands. The process of oak mortality is linked to a number of factors. If mortality occurs on a local or regional scale, considering multiple years, we speak of oak dieback (Rozas & Sampedro, 2013). Oak dieback is triggered by a series or combination of events of various abiotic and biotic factors. Abiotic factors such as drought (Bouwman et al., 2025; Filippo et al., 2010) fluctuating water tables (Oosterbaan & Nabuurs, 1991; Schmull & Thomas, 2000), late spring frost and nutrient imbalance by nitrogen deposition (Thomas & Blank, 1996) all play an important role in historical and current oak decline. Biotic factors such as defoliation by larvae of phyllophagous insect, damage done by beetles and infestation of fungi,

al play a dominant role in oak decline (Moraal & Hilszczanski, 2000; Niemczyk et al., 2017; Thomas & Blank, 1996).

1.3 Occurrence and causes of oak decline in Europe

The earliest record of oak decline happened in north-west Germany in 1739-1748 (Thomas et al., 2002). This die-off was triggered by severe frost in the winter of 1739-40 (from Hausendorf, 1940; Thomas et al., 2002). Later in Germany from 1909 to 1940, oak decline was described to be caused by a combination of insect defoliation and either winter frost, summer drought or flooding, and with oak mildew (*Erysiphe alphitoides,* syn*. Microsphaera alphitoides*) (Blank, 1997; Wachter 1999; Thomas et al., 2002). The occurred stress was followed by attack of pathogenic fungi (*Armillaria*) and oak Splendour beetle (*Agrilus biguttatus*) which both occur on less vital trees, and delivered the final event to cause mortality (Hartmann and Blank 1997; Hartmann 1996; Thomas et al., 2002). In Poland, an increase of oak mortality was observed from frost damage after 3 consecutive winters form 1939 until 1942 (Thomas et al., 2002; Turok et al., 1997). In the UK from 1920 until 1924 oak decline occurred after severe droughts, followed by insect defoliation and infections from pathogenic fungi (Gibbs & Greig, 1997; Thomas et al., 2002). In France decline occurred from 1921 until 1926 and from 1942 until 1950 (Turok et al., 1997). These episodes where presumably triggered by a combined effect of insect defoliation, droughts and frost (Thomas et al., 2002; Turok et al., 1997) In southern Sweden climate change is the leading factor for oak decline (Krutovsky et al., 2025) see figure 2 for an overview of oak decline. Pedunculate oak decline is always caused by a combination of harsh climatic conditions, which weaken trees and enhance disease and pest succession.

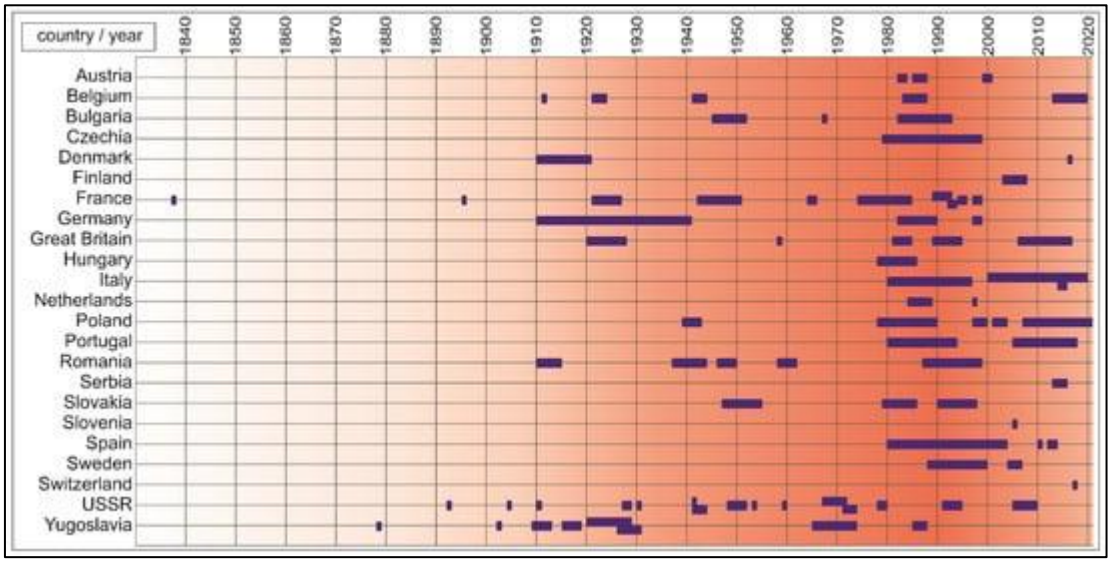

Figure 2: Overview of oak decline in Europe. Length of the bar represents the length of the decline (Macháčová et al., 2022).

1.4 Oak decline in the Netherlands: causes & mechanism

In the Netherlands there is 65.471 ha of oak forest (17,5 % of total forest surface) (Schelhaas et al., 2022). The Dutch forest inventory indicated that 11,7% of oak forest has as reduced vitality (Schelhaas et al., 2022). Oosterbaan (2014) has found that one third of 50 examined oak forests shows severe mortality with mortality rate of 20-60% (Oosterbaan, 2014). Oak decline occurred from 1984-86, due to a wet spring and dry summer, trees suffered from waterlogging followed by defoliation and pathogenic fungi (Oosterbaan & Nabuurs, 1991; Turok et al., 1997). Waterlogging resulted in shallow root formation and higher root mortality (Oosterbaan & Nabuurs, 1991). Additionally, research shows that pedunculate oaks react with the formation of small tree rings during or following a drought years (Bouwman et al., 2025; Oosterbaan, 2015). Oosterbaan (2015) shows that oak ring width is reduced in the years 1959, 1976, 1983, 1984, 1995, 2003, 2008, 2009 and 2010 by drought years on various sites in the Netherlands.

Additionally nutrient imbalances are secondary factors to weaken vitality (Lucassen et al., 2014; Oosterbaan, 2014a, 2015). In northwestern Europe including the Netherlands there is excessive deposition of nitrogen compounds from agriculture and industry. Nitrogen compounds have a complex effect on the environment but primarily acidify the soil creating nutrient imbalances. This nutrient imbalance has led to aluminium buffering and high Al/Ca ratio, causing the loss of biodiversity (van den Burg et al., 2014; Weijters, Bobbink, 2000). Lucassen (2014) has shown that low kalium and magnesium concentrations, are correlated with a high mortality percentage in Dutch pedunculate oak forest (Lucassen et al., 2014). Kalium and magnesium are both important for tree physiology. Kalium is essential for the moisture uptake and transport. Magnesium is important to produce chlorophyll and photosynthesis. Hence explaining sensitivity to drought and low nutrient concentrations in leaves (Gibbs & Greig, 1997; Lucassen et al., 2014). Low nutrient concentrations in leaves, has led a cascading effect to the decline of various birds species (van den Burg et al., 2014). Due to mineral deficiencies in prey species, birds do not get enough minerals for successful hatching and raising their offspring (van den Burg et al., 2014). These factors are all motivations to restore forest soils, for additional information see appendix 1 and 2.

1.5 Acute and chronic oak decline

The process of oak decline can take multiple decennia, this is what we call chronic oak decline (Denman et al., 2010). There are examples where pedunculate oaks die rapidly in a few years, in literature this is often referred to as sudden oak death (SOD) or acute oak decline (AOD) (Brown et al., 2015; Denman et al., 2010; Eaton et al., 2015). In the US acute oak decline is caused by a pathogen (*Phytophthora ramorum*) and in England caused by the European boring beetle (*Agrilus biguttatus)* which thrives on warmer temperatures and nest in already weakened trees (Brown et al., 2015; Eaton et al., 2015). The beetle is also present in Dutch forest and an important factor to kill weakened trees (Moraal, 1997). The pathogen is known to have caused extensive damage in North America and is detected in Europe. Until now, it did not caused extensive damage in Europa, however it remains under observation (Eaton et al., 2015).

In the Netherlands, biotic and abiotic factors are known to be influenced by climate change (Visser, 2005). The climate in the Netherlands is already changing, 2023 was the warmest (11,8 °C average) and wettest (1153mm precipitation) year ever recorded, since 1910 (KNMI, 2024). The average precipitation in 1910, consisted of 694 mm per year, this average has risen to 875 mm by 2022. That is an increase of 26% over a span of 113 years (Compendium voor de Leefomgeving, 2023b). Figure 3A shows the graph of Dutch average temperature, showing an increase of average temperature (Compendium voor de Leefomgeving, 2023a), figure 3B shows the graph for Dutch average precipitation, showing an increase in average precipitation (Compendium voor de Leefomgeving, 2023b). Climate change has an effect on biotic factors for instance the number of pest insect and their peak, this response is difficult to predict and varies on a case-by-case basis (Jactel et al., 2019). It is common for a number of caterpillars to defoliate the first flush of leaves e.g. the winter moth (*Operophtera brumata*), of which reports of severe infestations have increased (Oosterbaan, 2014). Furthermore the European oak leafroller (*Tortrix viridana*) and in warmer regions the gypsy moth (*Lymantria dispar*) are common to defoliate the first flush of leaves (Eaton et al., 2015; Thomas et al., 2002).

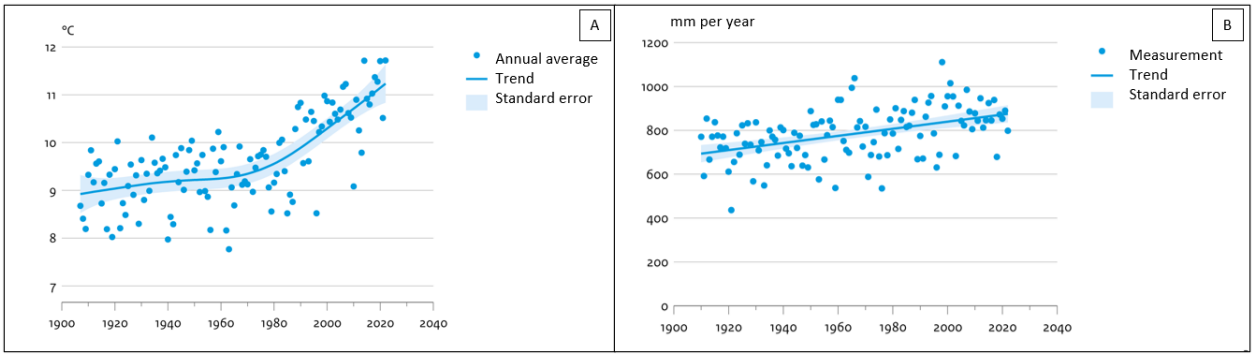

Figure 3: A: Dutch average temperature for five main meteorological stations in the Netherlands in degrees Celsius, 1910-2022. B: Dutch average precipitation for 102 meteorological stations in mm per year, 1910-2022. Source: (Compendium voor de Leefomgeving, 2023a) (Compendium voor de Leefomgeving, 2023b).

1.6 Research approach

This study aims to investigate long-term growth trajectories of pedunculate oaks, and annual growth- response to climate, by using dendrochronology. Dendrochronology is the scientific method used for dating and analysing the characteristics of annual growth rings of trees (Krutovsky et al., 2025). The subtle differences in growth dynamics provide direct evidence of years with favourable growing conditions versus periods with growth reduction. The width and structure of tree rings are directly influenced by climatic factors such as temperature, precipitation, and drought. This sensitivity allows dendrochronology to serve as a natural archive of historical climate variability (Jevšenak & Levanič, 2015; Oosterbaan, 2015). By studying tree rings, scientists can explain the impact of climate conditions and ecological changes on trees growing in different context. Losseau (2020) used dendrochronology to uncover an interplay of climate events causing oak decline in Belgium (Losseau et al., 2020). Gagen (2019) used

dendrochronology to determine acute and chronic oak decline in the united kingdom (Gagen et al., 2019). Both authors proved that climate extremes can significantly reduce growth rates in pedunculate oaks (Gagen et al., 2019; Losseau et al., 2020).

Given the historical background, pedunculate oak decline may result from a combination of unfavourable conditions which have affected oak growth in the past or directly before dying-off. This study we will use tree-ring data from dead and vital pedunculate oaks growing at two sites in the same forest to retrieve differences in growth patterns across the lifetime of these oaks. Climate-growth relationships will be determined to assess climate factors that mainly affected growth of in living and dead oaks. Special attention will be given to growth in reaction to extreme climate events such as drought and frost. The goal of this research is to analyse the annual ring width variation of dead and vital pedunculate oaks, detect periods of differences and link it to changes in climate-growth relationships or occurrence of climate extremes. We aim to answer the questions:

1. How do long-term growth patterns differ between dead and vital pedunculate oaks and when did oak decline start at the two study sites?
2. Which climate factors mainly determine the growth of living and dead oaks at the two study sites?
3. How do years with extreme growth depressions link extreme climate events in living and dead oaks at the two study sites?

The corresponding literature-based hypothesis is that: Dead pedunculate oaks exhibit significantly reduced growth rates and greater sensitivity to climate extremes compared to living oaks (Gibbs & Greig, 1997; Oosterbaan, 2014a, 2014b; Thomas et al., 2002; Weijters, Bobbink, 2000).

2.0 Methods

2.1 Study sites

The province of Gelderland has started an experiment to restore acidified forest see appendix 1 and 2 for additional information using rock dust. In 2020 the Radboud University together with Bware research center has set up an experiment with rock dust to restore the forest soil nutrient balance. The experiment is performed on ten locations on the Veluwe in the centre of the Netherlands (Figure 4). All locations had a severely acidified topsoil, with pH ranging from 2.5 to 4.0. The sites all comply with the following criteria: the location is in an old-growth pedunculate oak forest (H9190) consisting of mature dominant trees. Pedunculate oak is the dominant tree species. Plots within one location have similar soil structure, relief, and vegetation. The locations are well accessible. Each location consists of three plots of 0.5 ha: one control plot and two plots treated with rock dust. They made use of two distinct types of rock dust. One plot is treated with Soilfeed, this is rock dust made from left over rock from Norwegians mines. The second treatment plot is treated with Eifelgold. This rock dust is already available for commercial use and contains more phosphor.

Five locations contain undergrowth with blueberries (*Vaccinium myrtillus*), and five locations have no undergrowth. So, in total, there are three treatments, with ten plots each, half with/without blueberries. The plots are 70x70m and marked with colour coded poles see table 1. The treatment plots are enriched with ten tons of rock dust per ha, applied by hand or made use of a gritter and wheelbarrow. Within each plot, a fence is placed to look at the effect of grazers.

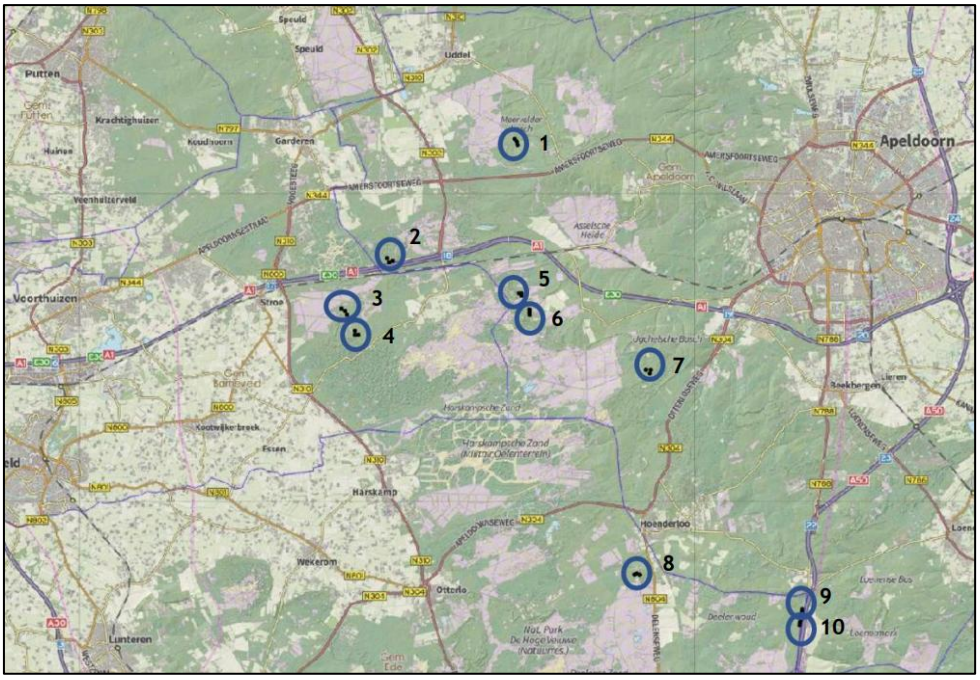

Figure 4: The 10 locations located in the province of Gelderland the Netherlands. Used for the experiment, each location contains 3 plots including 3 treatments. Source: (Weijters et al., 2020)

Rock dust should have a recovering effect on the forest soil, undergrowth and should make pedunculate oaks become more vital (Weijters et al., 2020). Previous studies have shown that its takes more than three years before the effect of rock dust is measurable in the soil (Weijters et al., 2020). We assume there is still no to not measurable effect in the growth of pedunculate oaks on the treatment plots. Therefore, this study will focus on the growth of pedunculate oaks growing in the control plots see figure 5 conceptual model for the effect of rock dust.

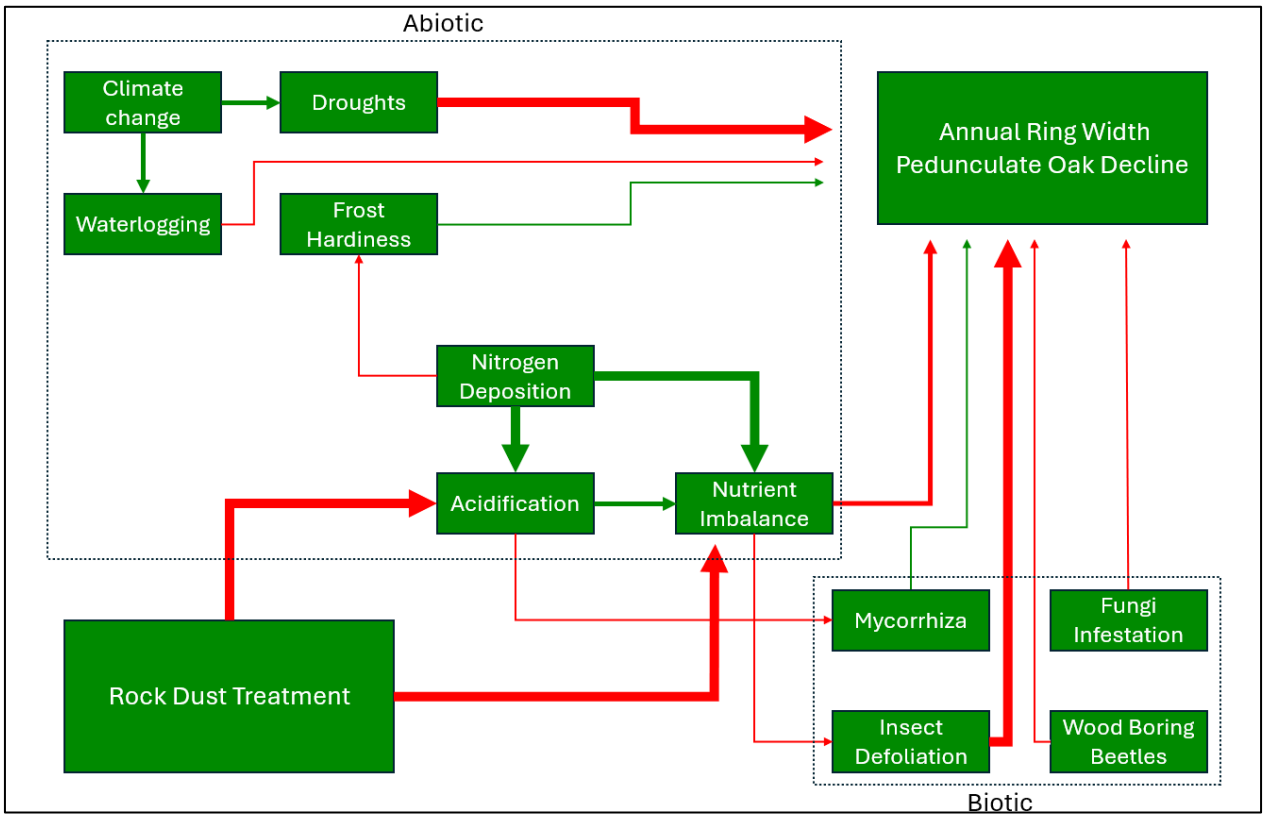

Figure 5: Conceptual model of pedunculate oak decline. Green arrows represent a positive effect and red arrow represent a negative effect. The weight of the line represents its significance to Pedunculate oak decline. Climate change has a positive effect on droughts and waterlogging, due to its increased change of occurrence. Both waterlogging and droughts have a negative effect on annual ring width. Frost hardiness on itself has a positive effect on annual ring width but is negatively influenced by nitrogen deposition. Nitrogen deposition has an increasing effect and therefore positive effect on acidification and nutrient imbalance. Rock dust treatment has a negative effect on acidification and nutrient imbalance. Acidification contributes to nutrient imbalance and therefore positive effect. Acidification has a negative effect on soil mycorrhiza. Nutrient imbalance has a negative effect on annual ring width and on insect defoliation. Insect defoliation on itself has a pronounced negative effect on annual ring width. Fungi infestation and wood boring beetles also have a negative effect on annual ring width of pedunculate oaks.

This study focusses on two sites, number five called Eikenheg, and number six called Heidenseberg, located in the Kootwijkerbosch. Eikenheg is without blueberries and Heidenseberg is with blueberries, see table 1 for further details. Both plots are owned and managed by Staatbosbeheer. Control plot location five is a transition plot, half of the trees consist of conifers. For additional information about altitude, soil and about the forest, see appendix 2.

Table 1: Information about the 2 locations, including 3 plots. Sites are in the province of Gelderland the Netherlands. Colour poles are poles that mark the corners of the plot.

Nr.	Name area	Name plots	Plot nr.	Treatment	Colour poles	Date of treatment	Blueberry	PH-NaCl
5	Eikenheg 52°11'16.1"N 5°48'57.7"E	Eikenheg	EH1	Control			No	3,42
			EH2	Soilfeed	White	14-02-2020	No	3,33
			EH3	Eifelgold	Red	18-02-2020	No	3,04
6	Kootwijkerbosch 52°10'57.9"N 5°49'13.7"E	Heidenseberg	HB1	Soilfeed	White	08-04-2020	Yes	3,4
			HB2	Eifelgold	Red	25-02-2020	Yes	3,32
			HB3	Control			Yes	3,57

2.2 Sample Collection for tree-ring research

Core samples are taken by using an increment borer, approximately knee height (60cm) from the forest floor (figure 6A). Within each control plot we have sampled thirteen trees. We have sampled seven dead trees and six vital (dominant/co-dominant (see figure 6B)) trees and took two core samples per tree. The second core was taken more or less perpendicular to the first one avoiding reaction wood. In total twenty-six trees and fifty-two core samples were collected. The dead trees were chosen randomly out of all dead solitary oaks with sapwood intact. We attempted to avoid sampling dead stems, from multi-trunked trees. Furthermore, we have measured the DKH (diameter at knee height), with a tape measure and measured tree height with a Nikon Forestry Pro. Within each plot trees will be inspected for cavities, fungus, or other insects' marks, to assess the presence of pest insects. The presence/absence will be inspected, the size and location. The location of the cavity of fungus is described as "at ground level" of "above ground". The cores were transported to the lab and airdried before mounted to wooden holders, a core microtome (*WSL, Switzerland*) was used to create a flat smooth surface. The ring width is measured accurate to the 100th mm using a combination of a Lintab digital positioning table and the software TSAP-Win (both Rinntech, Germany). To align the ring-width series with their correct dates, the samples were

visually cross-dated. First, we cross-date samples of the same trees, and later between trees.

Figure 6: A: Collecting core sample from HBX2, at approximately 60cm height at Heidenseberg. B: Forest at Heidenseberg, showing dominant/co-dominant dead and alive trees. Credits to Mathieu Decuyper for the help during fieldwork. Picture made during fieldwork in May 2024.

3.0 Analysis

Data analyses were done in R-studio (R version 4.2.2.). First, we aim to answer, "how do long-term growth patterns differ between dead and vital pedunculate oaks and when did oak decline start at the two study sites?" Therefore, the data is loaded with the read.rwl command. The two tree-ring series of the same tree were averaged into a mean ring-width series per tree. Boxplots are made to visualize and compare the mean ring width, differences per category (dead/living) and per site. The difference in mean radial growth will be evaluated using a two sample T-test. To exclude age-related growth trends in the ring-width series all series were detrended using a spline of thirty years with the function 'detrend' from the 'dpIR' package (Bunn, 2008).

COFECHA is a widely used computer program in dendrochronology for checking the quality of cross dating between ring-width series by applied correlation analyses. It ensures accuracy by statistically analysing and detecting errors in the sequence of ring widths, facilitating the construction of correctly dated chronologies for climate studies and historical research. The cross dating is checked using COFECHA (Holmes, 1983).

For each tree we calculated the Basal area increment (BAI) from annual ring-widths and visualized it as annual BAI series and as cumulative growth trajectory. To do so, we matched diameter at knee height (DKH) data with tree-ring width (TRW) data and adjusted for bark thickness. Then we calculated BAI using the bai.out function. We generated cumulative growth in square centimetres and plotted the overall growth trends (Klesse & Bigler, 2025). By aligning cumulative growth data by cambial age, we normalized comparisons across trees.

To determine whether dead and vital trees differ in their annual growth variation along their growth trajectories we performed a principal component gradient analysis (PCGA). The detrended annual growth trajectories were analysed using a PCGA with the package 'dendRoLab' (Buras et al., 2020). This PCGA will cluster the individual trees based on the similarity of their growth trajectories. The Wilcoxon rank test will be performed on the first and second PCA axis to see whether the two categories are significantly different. Finally, the package 'cluster' and 'dendextend' are used to visualise the outcome with a Hierarchical Gradient Analysis (HCA). The plots will be colour coded to visualize the outcome and grouped in the HCA to reveal subgroups.

To answer the question which climate factors mainly determine the growth of living and dead oaks at the two study sites. We analysed climate-growth relationships using detrended-TRW data alongside temperature and precipitation data from the meteorological station of de Bilt. This station provides data since 1901 and homogenized for research purposes. After adjusting the climate data for correct units, we use the treeclim package to perform correlation analyses. The correlations of climate and TRW are calculated per month, including the growing season and several months before. So, from January until September and July until December of the previous year. Secondly, we examined how monthly climate variables influenced tree growth from 1927 to 2023 with a moving window of 25 years.

We used the "dcc function" for correlation and moving window correlation analyses (Zang & Biondi, 2015). Visualization with ggplot2, the influence of temperature and precipitation on tree growth. For ease of use in other software, we exported the TRW data to CSV, providing a view of climate impacts on tree growth.

Finally, we answer the question how do years with extreme growth depressions link extreme climate events in living and dead oaks at the two study sites? Therefore, we identified pointer years. Pointer years are years with a decrease or if increase of growth on stand level and can indicate the start of growth decline. Pointer years are determined if at least 75% of the stand has the same reaction to an event of at least 10% narrower or wider ring widths than in the previous year (van der Maaten-Theunissen et al., 2015). The pointer years is calculated with BAI data to compare growth declines or decreases. We have used the package 'point.res,' with a moving window of seven. So we are able to include recent years of growth (van der Maaten-Theunissen et al., 2015). Once the pointer years are determined we compare the negative years to quantified data to determine the cause of the negative pointer year. We have compared the negative pointer years to winter temperature values (KNMI, 2025a), summer temperature values (KNMI, 2025b), annual average precipitation(Compendium voor de Leefomgeving, 2023b) and number of report of heavy infestation of the winter moth (Oosterbaan, 2014). Temperature data originates from meteorological station the Bilt, the sum of precipitation is calculated as annual average from meteorological stations across the Netherlands.

4.0 Results

4.1 Tree-Ring Chronologies Eikenheg & Heidenseberg

The chronology of Eikenheg shows a varying alignment of growth trajectories. During their juvenile years, alle trees show different growth patterns. The patterns align from approximately 1960ies onwards. The dead trees start to deviate from the living trees beginning in the 1980ies and die in 2001, 2005, 2006, 2007, 2008, 2010 and 2015 (figure 7A & figure 8). At Eikenheg the six living trees were on average 78.8 years old, mean radial growth was 1.99mm per year and their mean DKH was 38,36cm. Their growth spanned between 1927-2023. The seven dead trees had an average age of 66.7 years, mean growth of 1.46mm per year and mean DKH of 23,98cm. Their growth spanned between 1928-2015. Living trees at Eikenheg are older, grow faster, and have a larger diameter compared to dead trees, which started declining in the 1980s before dying between 2001 and 2015.

The chronology of Heidenseberg shows a perfect fit. Only the first 10-15 years are less synchronized. The dead trees show a stronger average growth than the living trees. After a negative growth year in 1992 the dead trees do not recover as sufficiently as the living trees, they show a lower average growth and decline until mortality in 1994, 2008, 2009, 2012, 2013, 2016 and 2021 (figure 7B & figure 8). At Heidenseberg the six living trees have an average of 93.3 years old, mean growth of 1.18mm per year, mean DKH of 25,8cm and height of 14,45m. Their growth spanned between 1928-2023. The seven dead trees had an average age of 80.1 years old, mean growth of 1.23mm per year and mean DKH of 21,6cm. Their growth spanned between 1928-2021. At Heidenseberg, dead trees initially grew faster but declined after 1992, whereas living trees, despite slower growth, were older and had a slightly larger diameter.

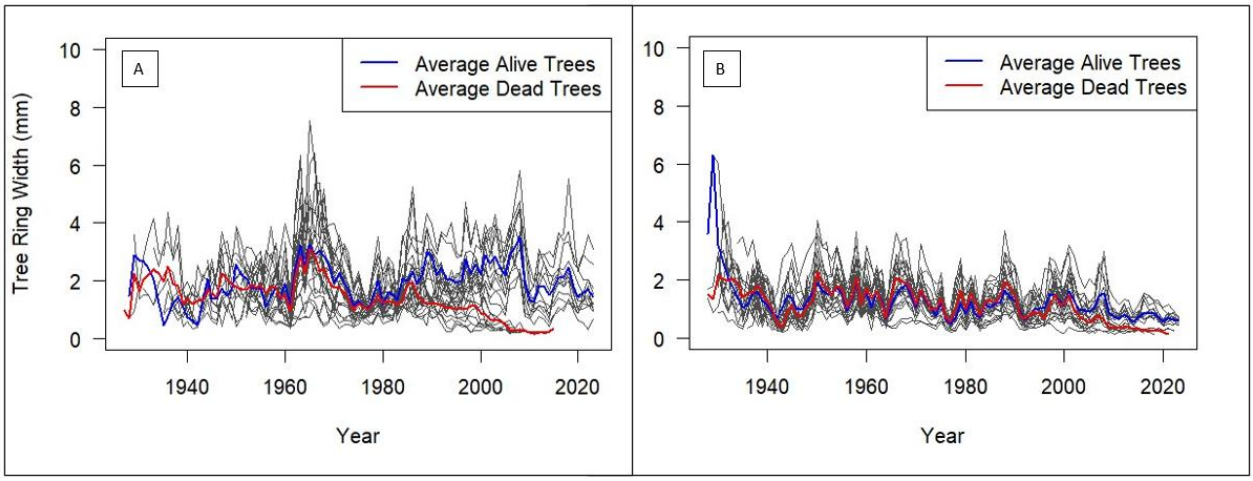

Figure 7: A: Chronology of annual radial tree ring width of pedunculate oak trees at Eikenheg. Black lines represent individual trees, colored lines represent average per group. B: Chronology of annual radial tree ring width of pedunculate oak trees at Heidenseberg. Black lines represent individual trees, colored lines represent average per group.

The actual tree age of both plots could be older. During sampling we hit the core only four times for both locations, with average age of 88,75 years old. Therefore, we could have missed some years at the start of the chronology of all categories. For the dead trees I also could have missed a year at the end of the chronology. Some of the sapwood was damaged because of decay, the actual age may be greater due to missing rings. However, both locations are coppiced trees and for both locations the oldest tree ring originates from 1927-28 sampled on DKH. We can reasonably assume the forest was last cut down in the beginning/mid-1920s. The trees at both sites may be older than recorded due to missed juvenile rings and decay-related losses in dead trees, but coppicing history suggests a forest regeneration period starting in the early to mid-1920s.

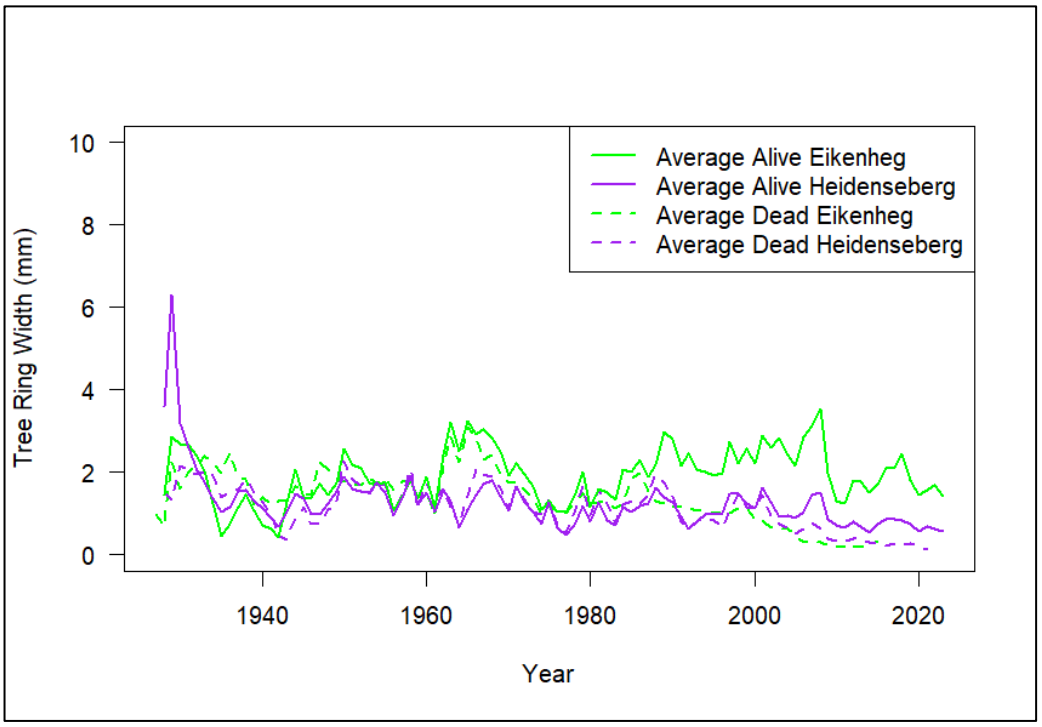

Figure 8: Chronology of average TRW per group, for Eikenheg and Heidenseberg. The green color represents Eikenheg, Purple represents Heidenseberg. Solid line represents vital trees, dashed line represents dead trees.

The Living trees at Eikenheg have a significant larger DKH as compared to the dead trees (two sample T-test) (p-value: 0.003). The average TRW of living trees at Eikenheg are significantly larger than the Dead trees in the same plot (two sample T-test) (p-value: 0.017).

The average DKH of living trees at Eikenheg is significantly larger than living trees at Heidenseberg, (two sample T-test) (p-value: 0.006). The average TRW of living trees at Eikenheg are also significantly larger than the dead trees at Heidenseberg (two sample T-test) (p-value: 0.0007).

The Living trees at Heidenseberg did not have a significant different DKH as compared to the dead trees (two sample T-test) (p-value: 0.13). The dead trees at Heidenseberg have a remarkable larger average TRW than the living trees but not significantly (p-value: 0.625) as seen in figure 9A and 9B. Living trees at Eikenheg exhibit significantly larger DKH and TRW compared to both dead trees at Eikenheg and trees at Heidenseberg. In contrast, at Heidenseberg, there are no significant differences in DKH between living and dead trees, and the higher TRW in dead trees is not statistically significant.

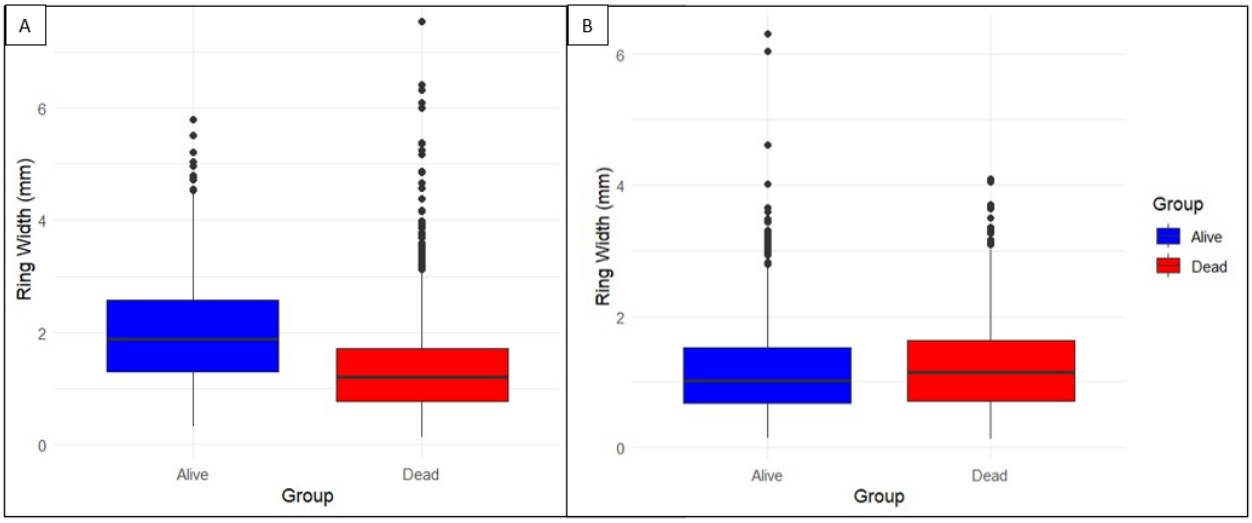

Figure 9: A: Boxplot of TRW for six living trees (mean growth of 1.99mm), and seven dead trees (mean growth of 1.46mm) at Eikenheg. Living trees showed significant larger growth (p-value: 0.017) B: Boxplot of TRW for six living trees (mean growth of 1.18mm), and seven dead trees (mean growth of 1.23mm) at Heidenseberg. Dead trees showed larger growth than living trees ns (p-value: 0.625).

The living trees at Eikenheg have significantly larger TRW than the living trees at Heidenseberg. Despite the trees at Heidenseberg where on average 14.5 years older. The dead trees at Eikenheg show a weaker growth in terms of smaller average TRW their whole lives, compared to the living trees. The dead trees at Heidenseberg show an anomaly, the dead trees have an average higher TRW than the living trees, however not significantly. Still the living trees have a greater DKH also due to thicker bark and older age.

4.2 BAI

The basal area increment, which represents the growth in total ring width surface area. The BAI shows large differences between the sites of Eikenheg and Heidenseberg. The DKH at Eikenheg is higher than that of trees at Heidenseberg. This difference is clearly reflected in the BAI growth curves of the living oaks see figure 10A and 10B. At Eikenheg, vital trees show a continuous increment of wood area, whereas at Heidenseberg, the increments of wood area remain constant. From 1980 onwards, the BAI at Eikenheg shows a rapid acceleration, resulting in a wood production rate that is two to four times higher than observed at Heidenseberg. Trees at Eikenheg exhibit a consistently increasing wood area growth, with a rapid acceleration after 1980, whereas trees at Heidenseberg show stable but lower BAI values, leading to significantly lower wood production.

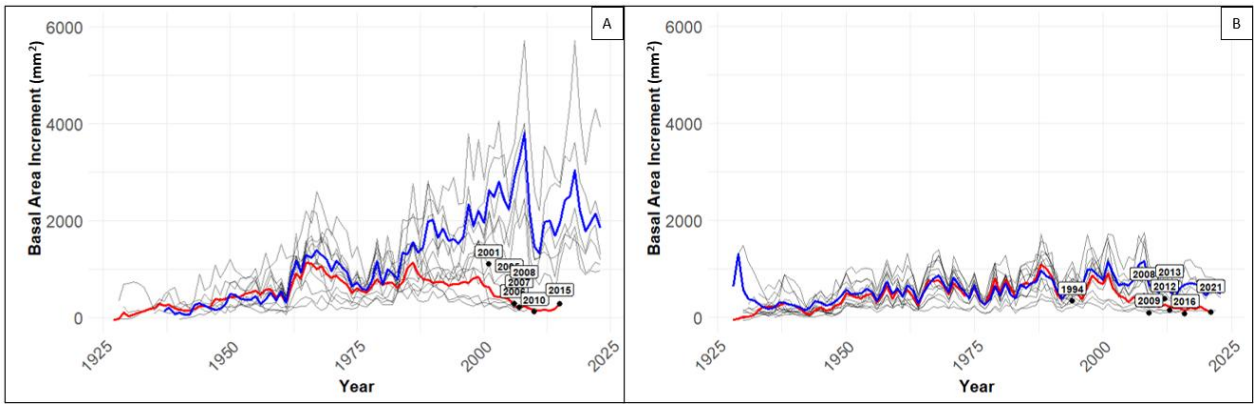

Figure 10: A: Basal area increment of Eikenheg in cm². Inserted year represents the mortality of a tree, being 2001, 2005, 2006, 2007, 2008, 2010 and 2015. B: Basal area increments of Heidenseberg in cm². Inserted year represents the mortality of a tree, being 1994, 2008, 2009, 2012, 2013, 2016 and 2021.

4.3 Cumulative Wood Growth Eikenheg & Heidenseberg

The cumulative growth is the accumulated volume of stem wood in a tree. Figure 11A shows the cumulative growth of Eikenheg. Here we see the living trees show a more exponential growth in wood volume, in the second half of their life. The dead trees show more constant growth which levels off as they die off. Figure 11B shows the cumulative growth of Heidenseberg. Here we see the same growth patterns for both the living and dead trees. At Eikenheg, living trees experience exponential growth in wood volume later in life, while dead trees stagnate before mortality. At Heidenseberg, both living and dead trees show similar, more stable, cumulative growth patterns.

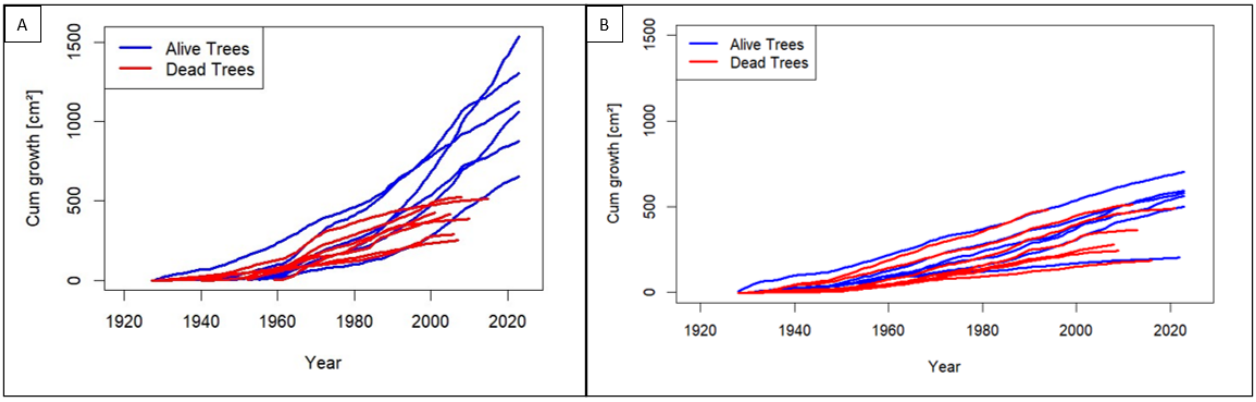

Figure 11: A: Cumulative growth in cm² at Eikenheg. B: Cumulative growth in cm² at Heidenseberg.

4.4 Cumulative Wood aligned to age Eikenheg & Heidenseberg

Figure 12A shows the same cumulative growth but aligned to the cambial age at Eikenheg. Were we notice the dead trees have a similar start but are not able to increase their cumulative wood growth and die-off. Figure 12B shows the same cumulative growth aligned to the Cambial Age at Heidenseberg. Here we notice the dead trees have slightly weaker but similar growth as compared to living trees. At Eikenheg, dead trees start with similar growth to living trees but fail to accelerate in wood production, leading to their mortality. At Heidenseberg, dead trees show slightly weaker but comparable growth trajectories to living trees.

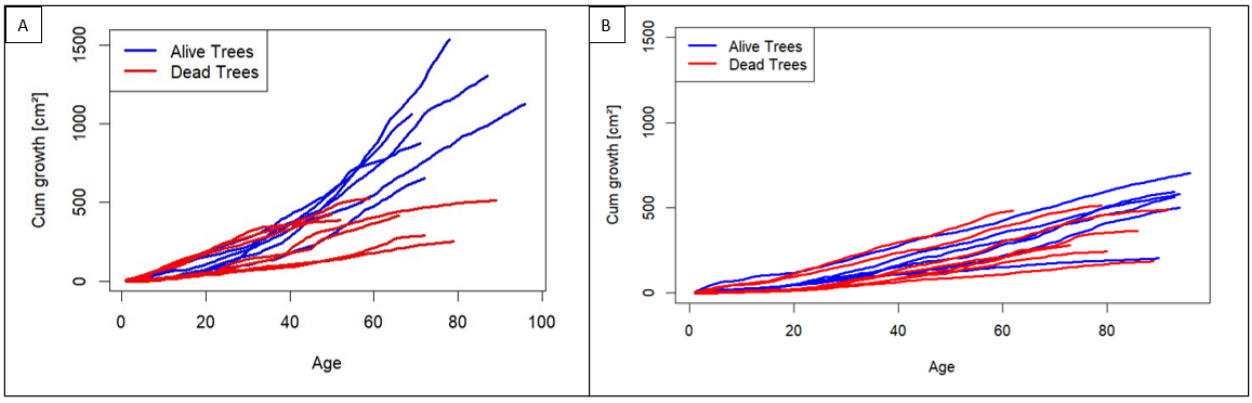

Figure 12: A Cumulative growth aligned to cambial age at Eikenheg. B: Cumulative growth aligned to cambial age at Heidenseberg.

4.5 PCGA & HCA Eikenheg

The principal component gradient analysis with detrended data shows there is no significant difference in growth trajectories between dead and alive trees in common interval from 1959 until 2001 at Eikenheg. Wilcoxon rank sum test on the first axis: W = 11, p-value = 0.1807 and second axis W = 12, p-value = 0.2343. Figure 13A shows the growth trajectories; here we see little to no group forming, although there is a trend at PC2 that living oaks tend to score higher values than dead ones. Still, this means that there is no interrelationship based on growth trajectories. The Hierarchical component analysis clusters the trees that have similar growth trajectories see figure 13B. Here we see one dead tree (EHD3) as outlier but no clear distinction between dead or alive trees. There is no significant difference in growth trajectories between living and dead trees at Eikenheg, as confirmed by principal component and hierarchical component analyses, though one dead tree (EHD3) stands out as an outlier.

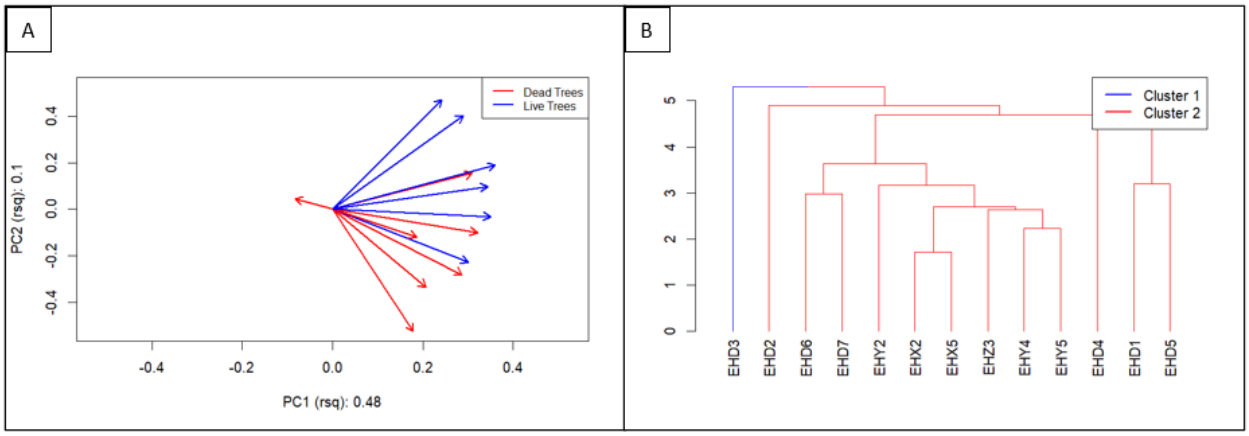

Figure 13: A: Principal Component Gradient Analysis, of all trees at Eikenheg. Direction of the arrow represents clusters based on their growth trajectories. B: Hierarchical Component Analysis Eikenheg. Colors represents clusters, based on their growth trajectories. Tree-ID represents their location, group and number. EH =Eikenheg, D=dead, X-Y-Z= Alive and tree number.

4.6 PCGA & HCA Heidenseberg

The principal component gradient analysis with detrended data shows there is no significant difference in growth trajectories between dead or alive trees in the common interval from 1936 until 1994 at Heidenseberg. Wilcoxon rank sum test on the first axis: W = 13, p-value = 0.2949 and second axis W = 10, p-value = 0.1375. Figure 14A shows the growth trajectories; here we see some group forming. Still, this means that there is no interrelationship based on growth trajectories. The Hierarchical component analysis clusters the trees that have similar growth trajectories see figure 14B. Here we see a small cluster of four trees but there is no clear distinction between dead or alive trees. Growth trajectories at Heidenseberg do not significantly differ between living and dead trees, as confirmed by principal component and hierarchical component analyses, though some minor clustering is observed.

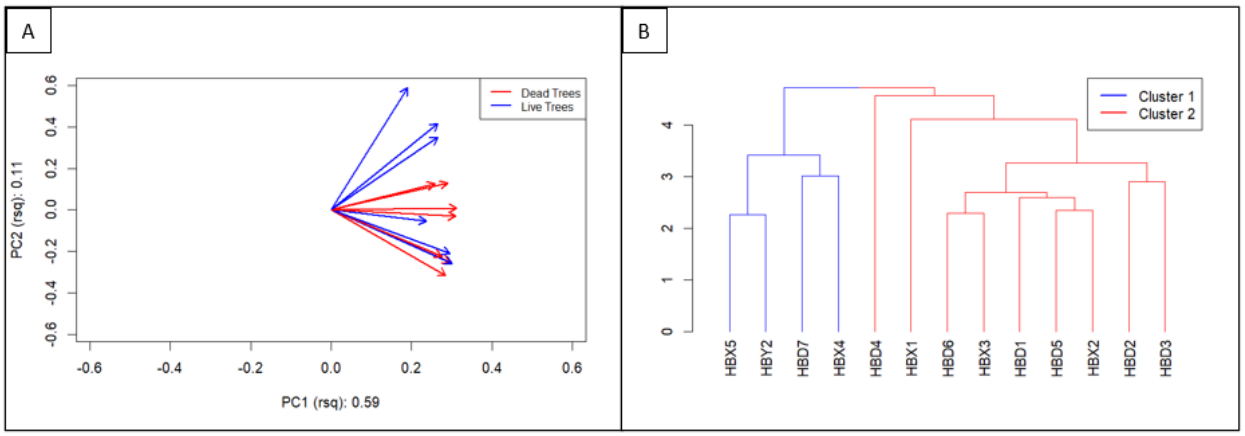

Figure 14: Principal Component Gradient Analysis, of all trees at Heidenseberg. Direction of the arrow represents clusters based on their growth trajectories. B: Hierarchical Component Analysis Heidenseberg. Colors represents clusters, based on their growth trajectories. Tree-ID represents their location, group and number. HB =Heidenseberg, D=dead, X-Y= Alive and tree

4.7 PCGA & HCA Eikenheg/Heidenseberg

The principal component gradient analysis for both locations show no distinctive group forming based on their growth trajectories see figure 15A. The Wilcoxon rank sum on the first axis W = 83, p-value = 0.9798, and on the second axis W = 66, p-value = 0.3744. This means that there is no interrelationship based on growth trajectories. The Hierarchical component analysis clusters the trees that have similar growth trajectories see figure 15B. Here we see a cluster of nine trees from Heidenseberg, including dead and alive trees. The second cluster has as subgroup from five dead trees from Eikenheg. Still there is no clear distinction between dead or alive trees. Growth trajectories do not significantly differ between locations or between living and dead trees. While clustering occurs, it is not based on mortality status, confirming no strong interrelationship in growth patterns.

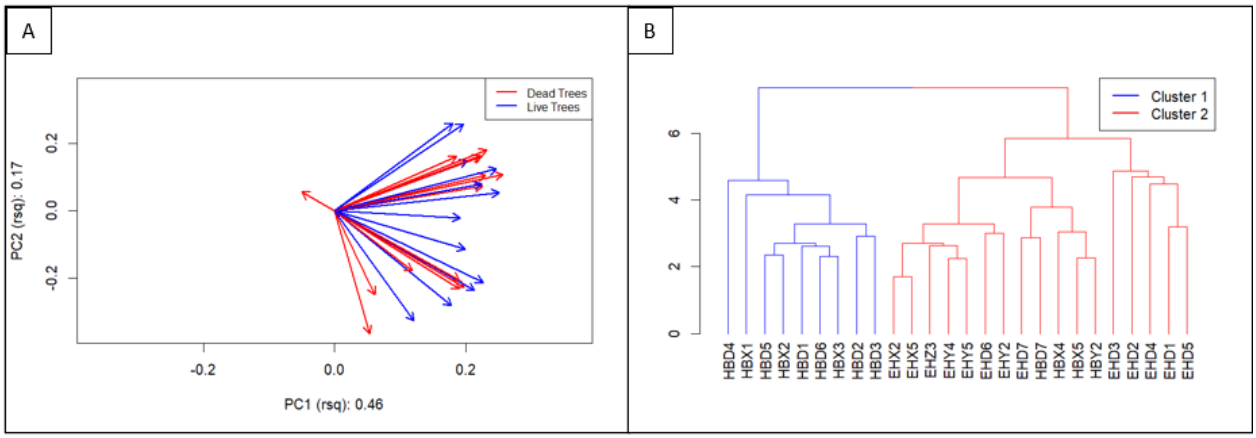

Figure 15: A: Principal Component Gradient Analysis, Eikenheg and Heidenseberg combined. Direction of the arrow represents clusters based on their growth trajectories. B: Hierarchical Component Analysis Eikenheg and Heidenseberg. Colors represents clusters, based on their growth trajectories. Tree-ID represents their location, group and number. EH=Eikenheg, HB=Heidenseberg, D=dead, X-Y-Z= Alive and tree number.

4.8 Pointer Years Analysis

Eikenheg

There are several differences between the pointer years of the dead tree's vs the living trees at Eikenheg. The dead trees show one positive year: 1936, and only two negative years 1961 and 2011. Figure 16A shows the pointer years for dead trees at Eikenheg, table 2 shows an overview of the pointer years. The living trees showed more positive years: 1931, 1938, 1939, 1944, 1950, 1979, 1989, 1997, 2007, 2008 and 2018. The negative pointer years for the living trees are also more frequent: 1935, 1936, 1942, 1956, and 2020. Figure 16B shows the pointer years for the living trees at Eikenheg, and table 2 shows an overview of the pointer years. There are no overlapping pointer years between the two groups.

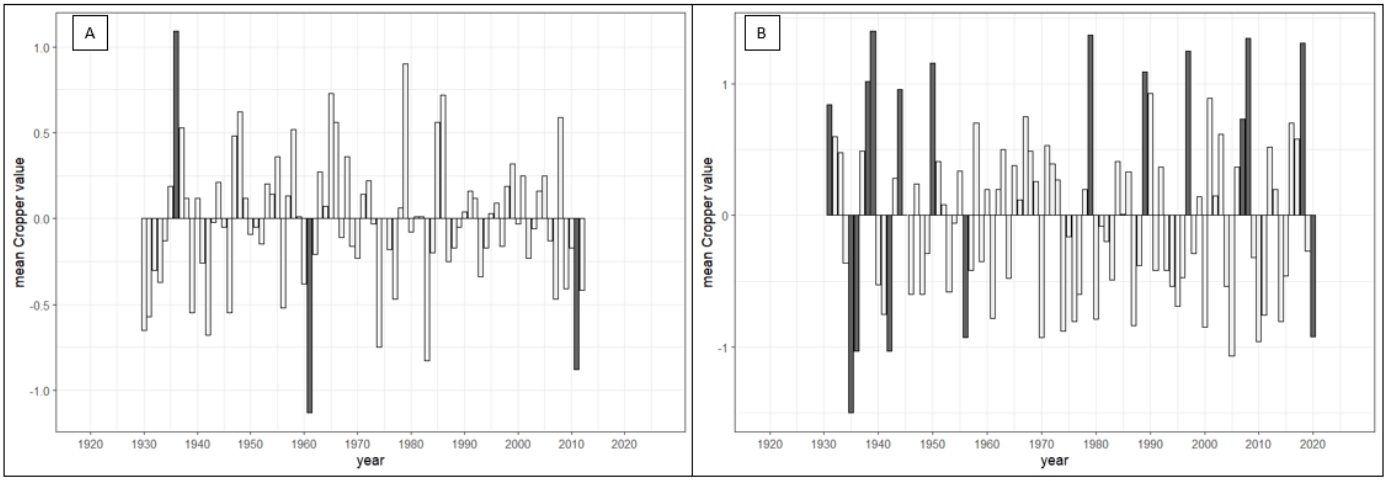

Figure 16: The mean Cropper value on the y-axis and the years on x-axis. The Bars in bold represent pointer years. A: Pointer years dead trees at Eikenheg, positive years: 1936. Negative years: 1961, 2011. B: Pointer years alive trees at Eikenheg. Positive years: 1931, 1938, 1939, 1944, 1950, 1979, 1989, 1997, 2007, 2008 and 2018. Negative years: 1935, 1936, 1942, 1956 and 2020.

Table 2: Positive and negative pointer years of trees at Eikenheg (EH).

Positive EH Dead	Negative EH Dead	Positive EH Alive	Negative EH Alive
		1931	
			1935
1936			1936
		1938	
		1939	
			1942
		1944	
		1950	
			1956
	1961		
		1979	
		1989	
		1997	
		2007	
		2008	
	2011		
		2018	
			2020

Heidenseberg

For Heidenseberg there are also several differences between the pointer years between living and dead trees. The dead trees showed five positive years: 1958, 1975, 1988, 1998 and 2013. There were eleven negative pointer years: 1943, 1956, 1964, 1970, 1977, 1983, 1992 and 1996. Figure 17A shows the pointer years for dead trees at Heidenseberg, table 3 shows an overview of the pointer years. For the living trees there are seven positive years: 1954, 1958, 1975, 1988, 2001, 2007 and 2008. There are five negative pointer years: 1956, 1964, 1977, 1992 and 2020. Figure 17B shows the pointer years for living trees at Heidenseberg, table 3 shows an overview of the pointer years. They have overlapping positive years in 1958, 1975 and 1988. Then there are overlapping negative years: 1956, 1964, 1977 and 1992.

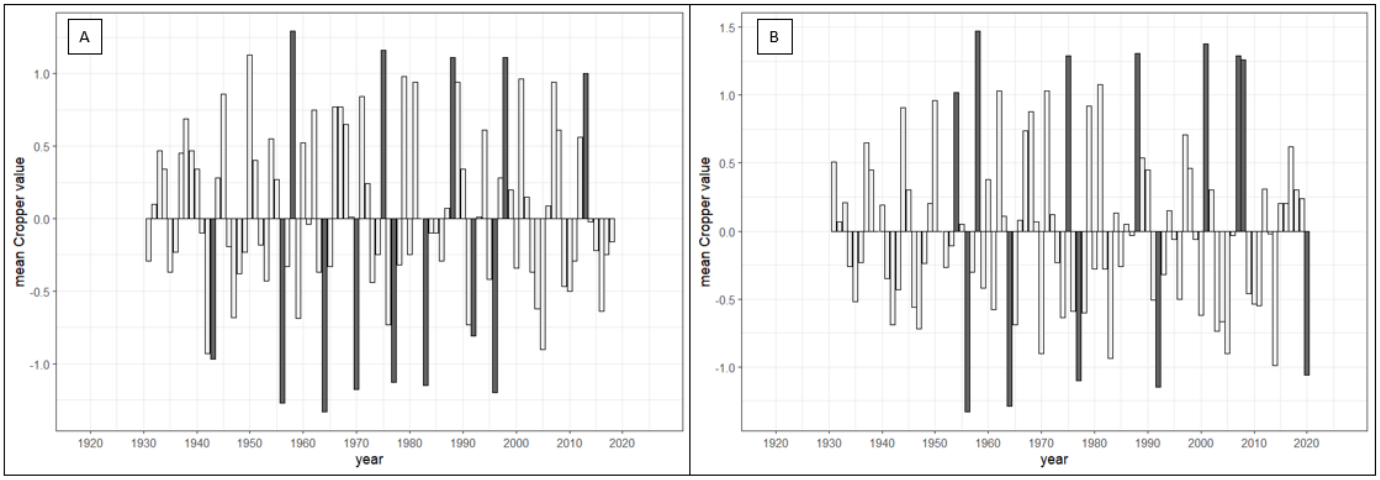

Figure 17: The mean Cropper value on the y-axis and the years on x-axis. The Bars in bold represent pointer years. A: Pointer years dead trees Heidenseberg. Positive years: 1958, 1975, 1988, 1998 and 2013. Negative years: 1943, 1956, 1964, 1970, 1977, 1983, 1992 and 1996. B: Pointer years Alive Trees Heidenseberg. Positive years: 1954, 1958, 1975, 1988, 2001, 2007 and 2008. Negative years 1956, 1964, 1977, 1992 and 2020.

Table 3: Positive and negative pointer years of trees at Heidenseberg (HB).

Positive HB Dead	Negative HB Dead	Positive HB Alive	Negative HB Alive
	1943		
		1954	
	1956		1956
1958		1958	
	1964		1964
	1970		
1975		1975	
	1977		1977
	1983		
1988		1988	
	1992		1992
	1996		
1998			
		2001	
		2007	
		2008	
2013			
			2020

Comparison between negative pointer years and extreme climate conditions & moth infestation

Table 4 shows an overview of all negative pointer years for all categories. Included in table 4 are values to quantify winters temperature, summer temperature, annual average precipitation and number of reports of heavy infestations of small winter moth. Temperature data originates from meteorological station the Bilt, the sum of precipitation is calculated as annual average from meteorological stations across the Netherlands (table 4).

The winter number is referred to as the Hellmann number (H-number), is a measure of cold winter conditions during the period from 1 November of the previous year to 31 March of the actual year. A day with an average temperature of -1°C over 24 hours contributes 1.0 to the H-number. The number is obtained by summing all 24-hour average temperatures below freezing (0°C) with the minus sign omitted (KNMI, 2025a). The sum of temperature is a measure of quantifying warm temperatures during the period from 1 April to 31 October of the written year. The sum of temperature is calculated by summing the average 24-hour temperature of each day that is above 18.0 °C. A day with an average temperature of 20°C over 24 hours contributes 2.0 to the sum of temperature. Summing all values will come to a total sum of temperature that allows us to quantify the year's heat (KNMI, 2025b). Yearly average precipitation is the yearly average precipitation in mm for that year in the Netherlands. Number of reports of heavy infestation by small winter moth is data from Oosterbaan 2014 (Oosterbaan, 2014).

Table 4: Negative pointer years for dead and alive trees at Eikenheg (EH) and Heidenseberg (HB). Hellmann number (H-number) is the sum of average temperature for 24 hours below 0 degrees Celsius from 1 November until 31 March. The number is classified as: H > 300 Severe cold, H > 160 Very cold, H > 100 Cold, H < 100 Mild, H < 40 Soft, H < 20 Very soft, H < 10 Exceptionally soft. The sum of Temperature is the sum of average temperature for 24 hours above 18 degrees Celsius from 1 April until 31 October. The H-number cell of 1964 contains an extra row. The year before 1964, being 1963, is the second coldest year ever recorded since 1901. The sum of temperature of 1977 and 1996 also contains an extra row. The year before 1977, being 1976, is the fourth warmest year ever recorded and the year before 1996, being 1995, is the third warmest year ever recorded since 1901. Yearly average precipitation (MM) is the Dutch average. Number of reports of heavy infestations of small winter month in the Netherlands is from Oosterbaan, 2014a.

EH Dead	EH Alive	HB Dead	HB Alive	H-number (indicator winter temp.)	Sum of growing season temperature	Annual average precipitation (MM)	Number of reports for heavy infestations of Small Winter Moth
	1935			20.9	57.3	799	No data
	1936			23.8	37.1	771	No data
	1942			333.5	37.0	696	No data
		1943		32.2	35.0	637	No data
	1956	**1956**	**1956**	222.9	6.2	778	2
1961				26.5	41.7	939	7
		1964	**1964**	**1963**: 337.2 **1964**: 111.6	55.9	698	19
		1970		141.3	67.5	816	0
		1977	**1977**	19.1	**1976**: 163.8 **1977**: 27.8	787	4
		1983		23.9	133.9	847	66
		1992	**1992**	33.6	102.8	862	9
		1996		150.5	**1995**: 169.7 **1996**: 55.5	631	144
2011				80.6	43.3	844	12
	2020		**2020**	0.1	145.6	853	No data

Unraveling pointer years

The additional data (table 4) reveals some indications for the pointer years. Over a period from 1901 to 2024.

- 1935 and 1936 did not show extreme temperatures or precipitation, offering no clear explanation.
- 1942 was the third coldest year on record, likely to explain the negative pointer years for living trees at Eikenheg and dead trees at Heidenseberg in 1943.
- 1956 was a very cold year, reflected in both locations and three categories.
- 1961 experienced heavy precipitation, possibly causing waterlogging/shifting water tables causing the negative pointer year for dead trees at Eikenheg.
- The 1964 pointer year at Heidenseberg may have resulted from the severe winter of 1963, which is the second coldest winter ever recorded.
- 1970 was both cold and wet.
- The warm year of 1976 likely influenced the 1977 negative pointer year at Heidenseberg.
- 1983 was a warm year, with quite many infestations of small winter moth.

- 1992 was a warm year however not exceptionally warm.
- 1996 was a cold year, after the third warmest summer since the start of the recording, paired with many reports of heavy infestations of small winter moth.
- 2011 had a mild winter, without further indications.
- 2020 was a very warm year following two consecutive warm years 2018 and 2019.

Cold winters and warm summers played a significant role in triggering pointer years, often shown in the next year.

4.9 Climate-growth relationships

Effect of mean temperature on oak growth

There are several months which show correlation with mean temperature at both Eikenheg and Heidenseberg. The living trees at Eikenheg show a significant positive correlation with temperature in May, meaning that warm conditions in the beginning of the growing season favor oak growth (figure 18A). The Living trees at Heidenseberg show a significant positive correlation with December indicating affinity with warmer conditions (figure 18B). The dead trees at Eikenheg have no significant correlation with temperature at all, see figure 18C. The dead trees at Heidenseberg have a significant negative correlation with temperature in July of the previous year, referring to negative growth reaction to hot previous summer and preference for warm winter conditions. Secondly, they show a significant positive correlation with temperature in February, see figure 18D. Living trees at Eikenheg benefit from warm Mays, while those at Heidenseberg respond positively to warm Decembers. Dead trees at Eikenheg show no temperature correlation, whereas dead trees at Heidenseberg are negatively affected by hot previous summers but benefit from warmer winters.

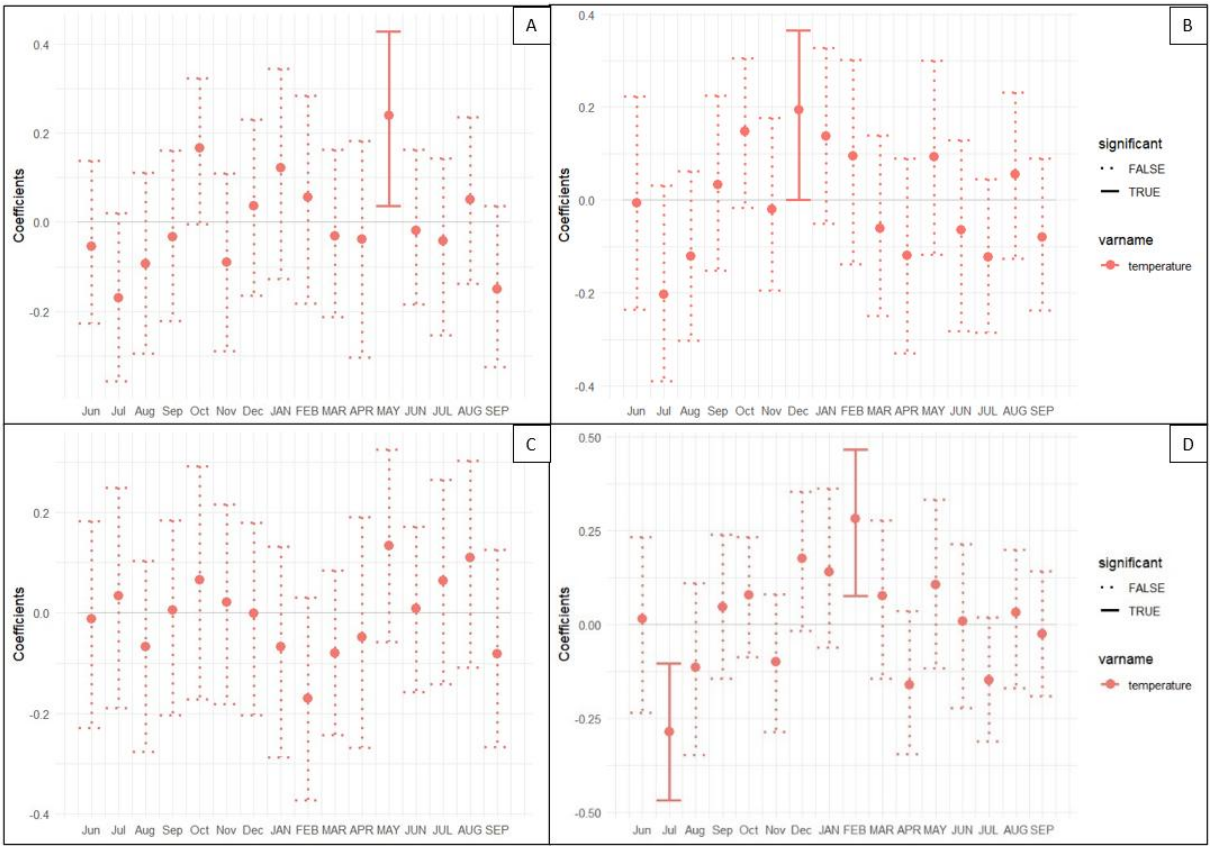

Figure 18: Temperature in correlation with detrended TRW. Climate data from De Bilt weather station. On the Y-axis the R-coefficient and on the X-axis the months. Capital letters represent this growing season, normal letters represent months from previous season. Solid line represents significant correlation, dotted-line non-significant. A: Eikenheg alive trees. B: Heidenseberg alive trees. C: Eikenheg dead trees. D: Heidenseberg dead trees.

Temperature correlation for the alive trees at Eikenheg show a positive correlation with temperature in May in the current season from 1980 till 2023, meaning they favor warm conditions in the beginning of the growing season see figure 19A. The alive trees at Heidenseberg show a positive correlation with temperature in December of the previous growing season from 1940 till 2023, indicating they favor warmer conditions in winter see figure 19B. The dead trees at Eikenheg show a strong negative correlation with temperature in January and February in the current season from 1940 until 2000, indicating negative growth respond to cold temperatures in winter see figure 19C. Dead trees at Heidenseberg show both strong positive and negative correlations. Positive correlation with temperature in February indicating an affinity with warmer temperatures in winter. Negative correlation in temperature in the previous season of Augustus from 1970 until 1990 and Juli from 1960 until 2020, indicating a delayed negative growth response to warm temperatures in summer see figure 19D. Living trees at Eikenheg grow better with warm Mays, while those at Heidenseberg benefit from warmer Decembers. Dead trees at Eikenheg struggled with cold winters, while dead trees at Heidenseberg showed both a preference for warm winters and a delayed negative response to hot summers.

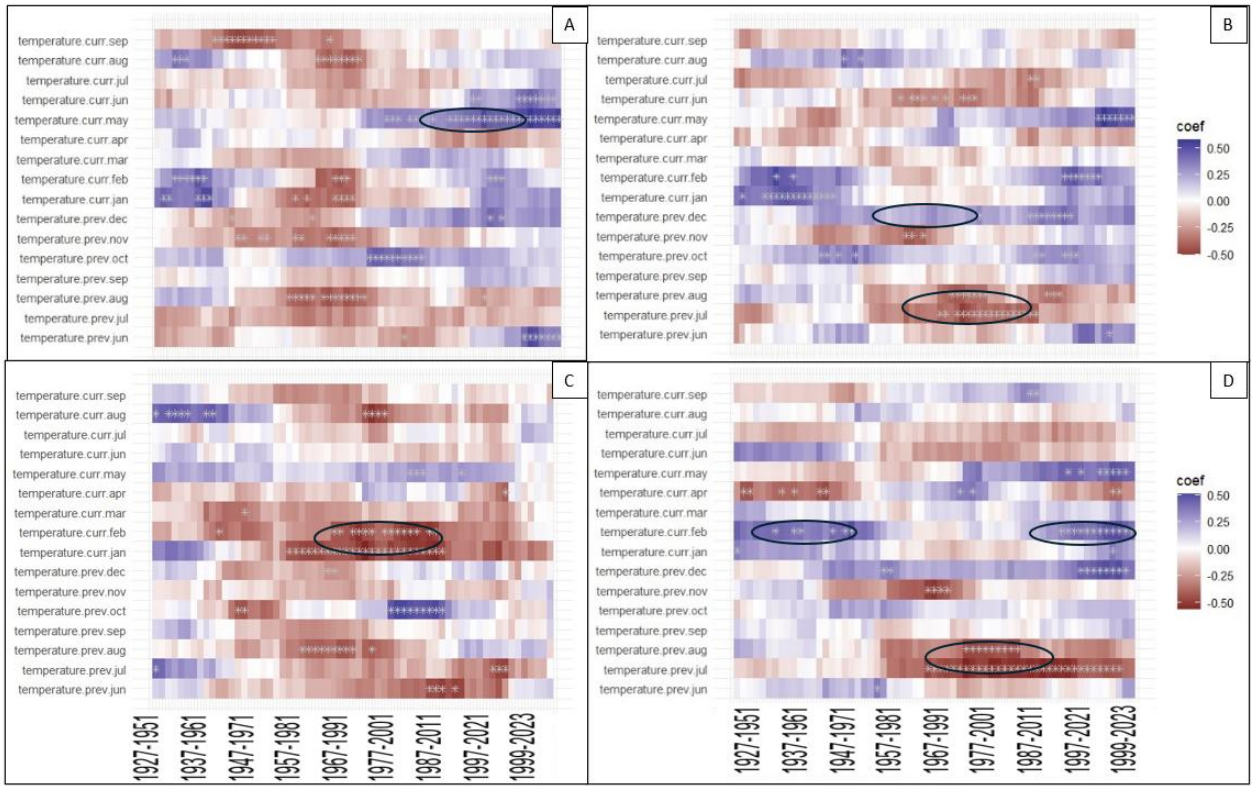

Figure 19: Temperature in correlation with detrended TRW. Climate data from De Bilt weather station. On the Y-axis the correlation with temperature in a specific month, from current season (curr.) of previous season (prev.). On the X-axis the chronological period of 1927-2023, each vertical square bar represents a correlation over 25 years and shifts every year. Colors represent coefficient, blue represents positive, red negative. Encircled periods represent strong positive or negative periods. A: Eikenheg alive trees. B: Heidenseberg alive trees. C: Eikenheg dead trees. D: Heidenseberg dead trees.

Effect of sum of precipitation on oak growth

There are several months which show correlation with mean precipitation at both Eikenheg and Heidenseberg (figure 20). The living trees at Eikenheg show a significant negative correlation with precipitation in October from the previous year indicating they favor less precipitation in autumn see figure 20A. The living trees at Heidenseberg have a significant positive correlation with July in the previous season, showing precipitation has positive influence on growth in summer see figure 20B. The dead trees at Eikenheg have no significant correlation with precipitation at all, although there is a negative trend with precipitation during the winter months see figure 20C. The dead trees at Heidenseberg show significant positive correlations for the months September and December in the previous year and march and September for the current growing season, indicating they favor precipitation in winter and late summer see figure 20D. Living trees at Eikenheg prefer drier autumns, whereas those at Heidenseberg benefit from wetter summers. Dead trees at Eikenheg show no precipitation response, while dead trees at Heidenseberg favor wetter conditions in winter and late summer.

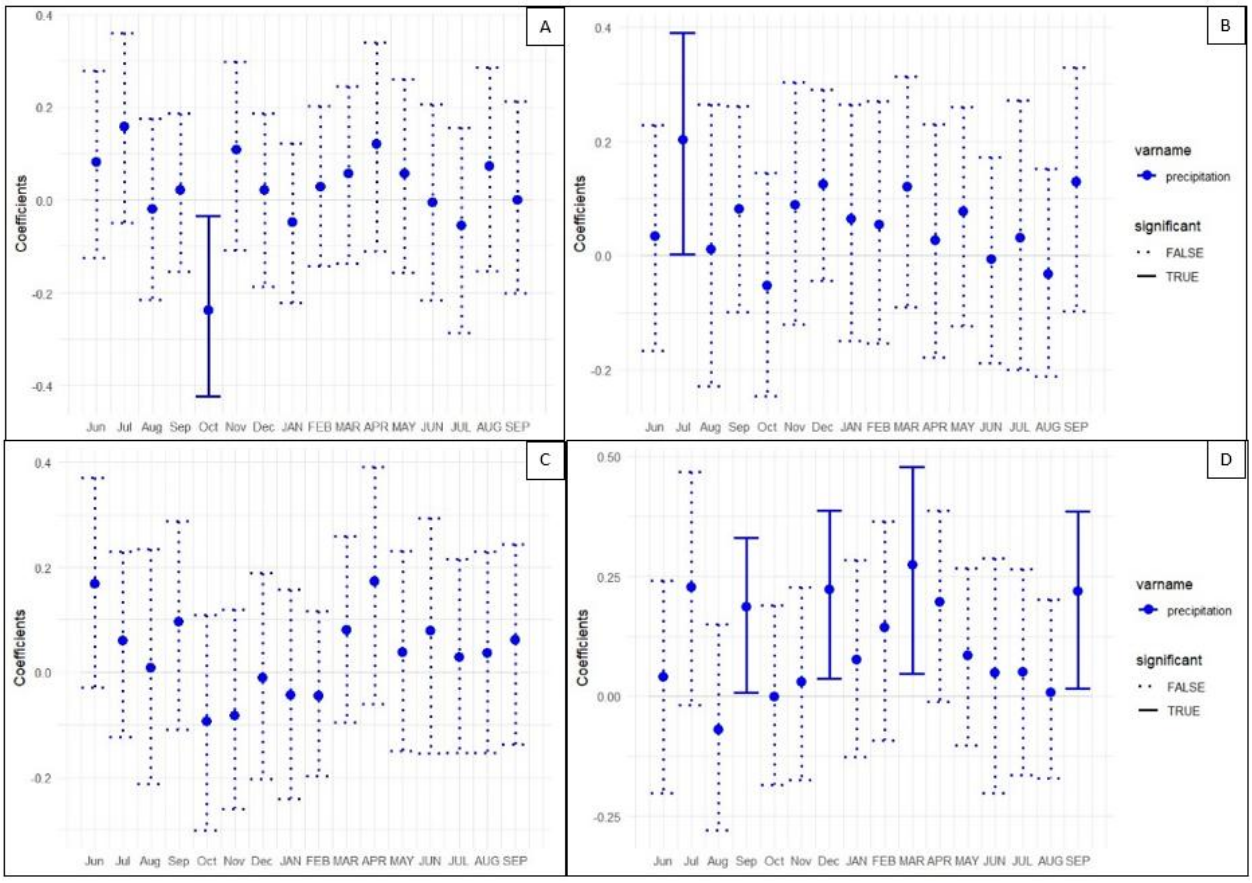

Figure 20: Precipitation in correlation with detrended TRW. Climate data from De Bilt weather station. On the Y-axis the R-coefficient and on the X-axis the months. Capital letters represent present growing season, normal letters represent months from previous season. Solid line represents significant correlation, dotted-line non-significant. A: Alive trees Eikenheg. B: Alive trees Heidenseberg. C: Dead trees Eikenheg. D: Dead trees Heidenseberg.

Precipitation in correlation over time showed the same pattern as before. The living trees at Eikenheg showed negative correlation with October precipitation from the previous season from 1920 until 1940, see figure 21A. The living trees at Heidenseberg showed similar negative correlation with precipitation although not significant. Here the July precipitation of the previous season showed a strong positive correlation from 1950 until 1980, showing an affinity with precipitation in summer see figure 21B. The dead trees at Eikenheg showed no significant correlation although precipitation in January and February is somewhat negative correlated and precipitation from April till July positively, showing they favor wet climate in spring rather than in winter see figure 21C. Dead trees at Heidenseberg show namely positive correlations. September and march of the current season show significant positive correlations. December and September of the previous season show also a significant positive correlation with precipitation see figure 21D. Living trees at Eikenheg consistently prefer drier autumns, while those at Heidenseberg favor wetter summers. Dead trees at Eikenheg show a weak preference for wetter springs, while dead trees at Heidenseberg strongly favor wetter conditions in both winter and late summer.

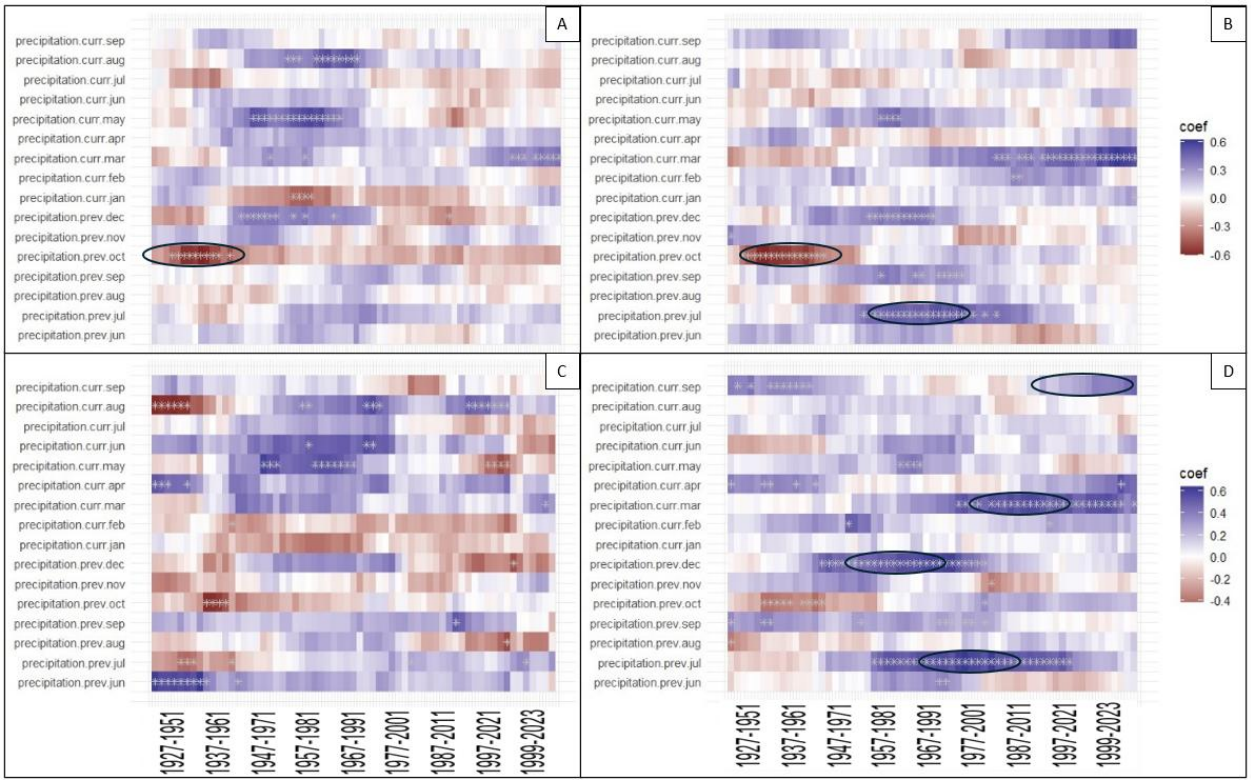

Figure 21: Precipitation in correlation with detrended TRW. Climate data from De Bilt weather station. On the Y-axis the correlation with precipitation in a specific month, from current season (curr.) of previous season (prev.). On the X-axis the chronological period of 1927-2023, each vertical square line represents a correlation over 25 years and shifts every year. Colors represent coefficient, blue represents positive, red negative. Encircled periods represent strong positive or negative. A: Alive trees Eikenheg. B: Alive trees Heidenseberg. C: Dead trees Eikenheg. D: Dead trees Heidenseberg. periods.

5.0 Discussion

In the Netherlands pedunculate oaks are declining and the direct cause is unknown. We want to look at the start and cause of oak decline. We aim to know how pedunculate oaks grow, respond to climate and whether trees die acute or chronic die-back.

5.1 Year of Growth Divergence between dead and living trees

The dead trees at Eikenheg start to deviate from the living trees from 1983 onwards, the growth stagnates until 1996. From 1996 onwards a drop in TRW, triggering die-off in 2001, 2005, 2006, 2007, 2008 and 2015. This corresponds with findings of TRW decline after a drought year in oak forest in the whole of the Netherlands (Oosterbaan, A. Bobbink, R. Decuyper, 2014). Both 1983, 1984 and 1996 are drought years known in literature as (Bouwman et al., 2025; Oosterbaan, A. Bobbink, R. Decuyper, 2014). These findings are also in line with results from another dendrochronological research on the Veluwe. Meijenfeldt (2023) found that dead trees near Woeste Hoeve (13km away) started to deviate from 1984/1985 onwards (Meijenfeldt, 2023). Finally these results match perfectly with earlier published literature review of Macháčová (2022) (figure 2), showing that pedunculate oak decline in the Netherlands occurred mid 1980ies and in 1996-1997 (Macháčová et al., 2022).

On average the trees take more than a decade to die, however EHD1 and EHD3 do die with rather strong TRW and visually show no longer period of decline, which is curious in comparison to other trees. For EHD1 we estimated to have missed some sapwood, which likely explaining the anomaly. EHD3 did die with strong TRW and became an outlier in the PGCA and HCA. However, there were no traces of bleeding and/or exit holes from beetles, which are strong indicators as described by Brown et al.,(2015) for acute oak decline (Brown et al., 2015).

The dead trees at Heidenseberg show a weaker recovery after a negative pointer year in 1992. 1992 was a negative pointer year for all trees at Heidenseberg. Similar results were found by Meijenfeldt (2023) both dead and alive trees at Woeste Hoeve (13km away) responded negative to 1992 (Meijenfeldt, 2023). They have continue to grow until the next negative year 2003. They did not recover sufficiently and subsequently died in 1994, 2008, 2009, 2012, 2016, 2021. In literature, the year 2003, 2008, 2009 and 2011 are also referred to as drought years, hence explaining the last measured year ring (Bouwman et al., 2025; Oosterbaan, A. Bobbink, R. Decuyper, 2014). Of which HBD3 and HBD5 do visually die rather fast. HBD3 decline in 6 years and HBD5 in 4 years. We estimated to have missed 1-2 years for HBD3 and 3-5 years for HBD5. Given the fact there were no traces of bleeding and/or exit holes from beetles, we have no assumption they died from an acute cause. Finally, while taking samples from dead trees we noticed there was still some form of life in HBD2. There were still some leaves at the trunk, indicating life in 2024. However, while analysing the samples it was shown that the tree ring came until 2021. This shows that the last visible tree ring is not a indicator of tree definitive mortality. The same applies for some of the living trees, HBX1 was

alive, but missed a year. The growth of this tree was so minimal, that it stacked a year.

5.2 Dead vs Alive

The Principal Component Gradient Analysis (PCGA) reveals no significant differences within the common interval of 1959-2001 at Eikenheg and 1936-1994 at Heidenseberg. This indicates that there is no substantial variation in growth trajectories. Although we see a trend that living trees tend to score higher values. The Hierarchical Component Analysis (HCA) reveals no categorical group formation. This suggests that the chronologies of all trees are similar, with no different group formation. At first, this can also be seen in cumulative wood growth and cumulative wood growth aligned to age. The cumulative wood growth showed similar wood accumulation. Secondly, Heidenseberg showed a matching chronology with all trees, giving no indication for group formation. Eikenheg showed more variance in the data resulting in less similar matching chronologies. This resulted in one outlier; however, this could be caused by crown suppression earlier during its life. The cored trees may not have been dominant for their whole their life and therefore had a divergent growth pattern.

5.3 Pointer Years

The pointer year analysis at Eikenheg showed no overlapping years between dead and alive group. It is peculiar to see that living group showed many more pointer years than the dead group. Although the chronologies did not match so well as expected, this could have an influence on the pointer year analysis. A pointer year is identified as 75% of the individual years show an anomaly (van der Maaten-Theunissen et al., 2015). If the chronology is going all over the place, it’s difficult for a pointer year to be identified.

The pointer year analysis at Heidenseberg showed a matching analysis with three positive years: 1958, 1975 and 1988, and five negative overlapping years: 1956, 1964, 1977 and 1992. Diving deeper into climate data, it reveals that pointer years are often expressed after a very cold or very warm year. The years 1942, 1943, 1956, 1963, 1964, 1970, 1996 are negative pointer years probably induced by low winter temperatures. Bouwman et al., 2025 and Oosterbaan, 2014 showed that 1976 is known to be a drought year, it is common for oak to respond a year later, explaining 1977 as negative pointer year (Bouwman et al., 2025; Oosterbaan, 2014). The years 1983, 1996 and 2020 were very warm years, likely explaining these negative growth years (Bouwman et al., 2025; Oosterbaan, 2014). Finally, Meijenfeldt (2023) has shown that pointer year 1992 was also a negative pointer year for trees at Woeste Hoeve (Meijenfeldt, 2023). However, the reason for 1992 being a negative year is not yet determined.

5.4 Climate-Growth Relationships of living and dead oaks

The alive trees at Eikenheg show a positive correlation with temperature in May. The living trees at Heidenseberg show a positive correlation with temperature in December. Following literature this fits with oaks being sensitive to overnight frost,

that is quite common in that period of the year, -especially in spring, while they flush their first leaves (Gosling et al., 2024; Oosterbaan, A. Bobbink, R. Decuyper, 2014; Thomas, 2008).

As mentioned pedunculate oaks can be somewhat late in there responds to climate (Oosterbaan, A. Bobbink, R. Decuyper, 2014). This is indicated by a small TRW the year after a precipitation deficit (Bouwman et al., 2025). This is also indicated by the significant negative correlation with temperature in July from the previous year at the dead trees at Heidenseberg. Heidenseberg is on top of a hill of fine-loam poor sandy soil, and therefore precipitation infiltrates the soil easily and there is a greater change of run-off of water.

Meijenfeldt (2023) showed that dead trees reacted less to environmental cues because they were in decline (Meijenfeldt, 2023). This outcome is in contrasts with the hypothesis and results of this thesis. Climate correlations have shown that dead trees had a stronger response to climate during their lifetime, however they did not show a response to environmental cues in their final life stage, when the growth level was strongly reduced.

All trees at Heidenseberg respond to temperature following the normal seasonal pressure; In the summer there is a negative correlation with temperature, in winter it is rather positive. Although the stress induced by climate is much stronger in dead trees, both positive and negative, than on living trees. The dead trees at Heidenseberg show a strong negative correlation with temperature in august and July from the previous year, starting already at 1983 until 2014. The year 1983 is known as a drought year; surprisingly the dead trees start to deviate only in 1992. Living trees have the same negative correlation, but less strong. A study performed with pedunculate oaks in Polen has found that spring growth is mainly driven by precipitation, while in summer and autumn groundwater levels play a more critical role, this could explain the negative reaction to temperature in summer and positive reaction to precipitation in spring (Krutovsky et al., 2025).

The dead trees at Eikenheg start to deteriorate in the early 1980’s. The start of the decline aligns perfectly with the negative correlations with the temperature of the current growing season in January and February from 1980 till 2010. This could indicate dead trees at Eikenheg suffered from frost damage and therefore became less vital and declined until dead. However, the decline also aligns with drought years like 1983 from literature (Bouwman et al., 2025; Oosterbaan, 2015). Other literature wrote; oak decline occurred from 1984-86, due to a wet spring and dry summer, trees suffered from waterlogging followed by defoliation and pathogenic fungi (Oosterbaan & Nabuurs, 1991; Turok et al., 1997). Climate data also reveals that 1985-87 where cold winters (KNMI, 2025a). This combination of events could explain the mixed outcome between plots.

It is peculiar that both locations have different correlations with temperature and precipitation. A possible explanation could be their geographical location. Eikenheg was a somewhat flat area, with traches of pond forming in winter. This could

indicate that trees at Eikenheg suffered from fluctuating water tables in winter, hence explaining the negative correlation with precipitation in October. Heidenseberg is on top of a high sand dune, therefore water tent to run-off and makes it more vulnerable to summer droughts, which is also confirmed by the positive reaction on precipitation in both dead and alive trees.

Where the trees at Heidenseberg follow the seasonal change in precipitation and temperature. The trees at Eikenheg show a negative correlation with temperature throughout the whole year from the 1960's until 1980's. But from 1980 onwards the correlation becomes more positive, this aligns perfectly with the increase of TRW and BAI. This also aligns perfectly with the increase of yearly average temperature due to climate change. Which increase rapidly from 1980 onwards (*Temperatuur in Nederland, 1907 - 2022*, 2023). Another possible explanation could be that the thinning of trees resulted in an increase of TRW. However, as we do not have data for the forest management in that area, it is impossible to underpin this explanation. The living trees at Eikenheg also have a negative correlation with precipitation in October of the previous year. The increase of yearly temperature could improve the fluctuating water tables situation, which results in stronger growth.

The dead trees at Eikenheg showed similar temperature correlations, although the dead trees suffered continuously from low temperature during winter. Based on temperature, we can assume that for the dead trees, the situation was not improved enough. Another possible explanation could be that some of the dead trees were sampled in a slightly hillier area just next to the control plot with living trees, because there were little dead trees in the control plot.

5.5 Role of Winter Moth

The dead trees at Eikenheg show a decline from the 1980's onwards. This decline aligns with negative growth induced by droughts. However, literature shows that in the mid 80's there were many recordings of Winter moth (*Operophtera brumata*) infestations. The drought induced stress pared with Winter moth infestation could have resulted in the deteriorations of pedunculate oaks (Oosterbaan, 2014). Defoliation by winter moth could also have contributed to trigger initial dead. Moraal (2010) and Oosterbaan (2014) showed that 1996, 1997, 2009 and 2010 are years with severe infestation of winter moth. Moth infestations often occur after warm years, which indicate that Winter moths respond well to high temperatures (Moraal, 2003; Oosterbaan, 2014b, 2015). Thomas et all (2004) has experimentally shown that repeated defoliation by Winter moths of pedunculated oaks resulted in a reduction of concentration of soluble sugars, reducing frost hardiness (Thomas, et al. 2004).

5.6 Rol of Nutrient Availability

Literature has shown that nitrogen in the soil can make trees more susceptible to frost. Especially night frost in spring can damage the first flush of leaves, inducing damage to the tree, reducing vitality (Skeffington & Wilson, 1988). Other

researchers have shown that less vital oaks forests often have soil nutrient imbalances (Lucassen et al., 2014).

Chemical analysis of the soil of various oak stands on the Veluwe including Eikenheg and Heidenseberg has shown that a very low soil pH was measured in the OH layer and in the top soil (Weijters et al., 2020). Furthermore, the Al/Ca ratio should be 2 mol/mol, above this ratio damage occurs to the vegetation due to aluminium toxicity (Weijters, M. Bobbink, 2000). At Eikenheg this ratio is only managed in the topsoil at 0-10 cm deep, below 10cm the ratio is 4/1 or higher. At Heidenseberg the ratio is 3,6/1 until 6,8/1 (Weijters et al., 2020).

Base saturation should be minimal of 20%. Below 20% there is a loss of species (Weijters, M. Bobbink, 2000). At Eikenheg this percentage ranges from 9,8-19,7%. Heidenseberg has a percentage of 9,4-13,2%, indicating an acidic environment (Weijters et al., 2020). So could say that there is a loss in species. This is problematic for the biodiversity.

Lucassen (2014) has shown that low kalium and magnesium concentrations, are correlated with a high mortality percentage in Dutch pedunculate oak forest (Lucassen et al., 2014). Kalium and magnesium are both important for tree physiology. Kalium is essential for the moisture uptake and transport. Magnesium is important to produce chlorophyll and photosynthesis. The vital Dutch forest in nature reserve the Maasduinen has an average kalium concentrations of 1200 µmoll/kg (Lucassen et al., 2014). Eikenheg has a kalium concentration of 344-471 µmoll/kg and Heidenseberg has a kalium concentration of 260-415 µmoll/kg. Indicating a severe kalium shortage (Weijters et al., 2020). Again, this is seen in the results, pedunculate oaks are sensitive to warm summers, when moisture uptake and transport is essential for survival.

The soil is very poor in basic cations and very rich in available aluminum. These conditions create an unfavorable environment for fine roots and ectomycorrhizal fungi, this can negatively affect the vitality of the trees. These conditions are highly unfavorable for the germination of young trees and understory of herbs leading to a loss of biodiversity. Hence contributing to drought sensitivity (Weijters et al., 2020).

To know the extent of unfavorable soil conditions, additional soil analyses and leaf nutrient concentrations can provide further insight. Future research can provide insights by monitoring changes in soil, vegetation, trees and soil fauna. To determine whether the application of rock dust in oak forest provides sufficient recovery.

6.0 Conclusions & recommendation

The decline of pedunculate oaks (*Quercus robur*) in the Netherlands is a gradual and complex process driven by a combination of abiotic, climatic factors, e.g. drought, frost, biotic factors, such as insect infestations, and site-specific conditions as defined by e.g. nutrient deficits in the soil. This study analyzed long- and short-term variation in growth patterns from dead and living oaks at two sites, Eikenheg and Heidenseberg, to understand mortality triggers and to evaluate the potential effectiveness of restoration measures like rock dust application.

Growth patterns differ significantly between dead and vital trees. At Eikenheg, declining trees showed lower growth throughout their lifespan, with a drop in tree-ring width (TRW) after 1983, leading to oak mortality between 2001 and 2015. At Heidenseberg, trees that failed to recover from the 1992 negative pointer year showed a steady decline, with mortality occurring between 1994 and 2021. Both locations show long-term growth decline and mortality after 15-30 years indicating chronic oak decline. This confirms that long-term growth stagnation and weak recovery after stress events are strong indicators of chronic oak decline.

Climatic variability contributes primarily to oak decline. At Eikenheg, negative correlations with winter temperatures suggest susceptibility to frost damage, while at Heidenseberg, rapid water runoff could have increased vulnerability to summer droughts. Severe winter moth infestations in the 1980s may have further weakened trees. Trees began deteriorating in the early 1980s and 1990s, coinciding with major droughts and cold winters.

Management recommendations

Soil conditions played a crucial role in oak decline, with factors such as low pH, high aluminum availability, and deficiencies in potassium and magnesium negatively affecting water uptake, photosynthesis, and root development. Given the severity of soil degradation, targeted restoration measures are necessary to enhance oak resilience. Future research should focus on assessing the effectiveness of rock dust application and other soil amendments in improving nutrient availability and soil structure.

In addition to soil restoration, revitalizing oak forests through replanting of nutrient rich-litter species could help enhance soil fertility, maintain structural diversity, and improve long-term forest stability. A more diverse forest structure can help mitigate drought effects by regulating microclimatic conditions, retaining soil moisture, and reducing water runoff. These measures, combined with long-term monitoring of soil properties, tree growth, and leaf nutrient concentrations, will be essential for guiding effective forest management strategies in response to climate change.

7.0 Acknowledgement

Vincent Wolf, Viktoria Greaser, Janna van Norel, Bai Klap, Zarah Tomesen, Katrien Verhoeven, Tom Steffens, Joost Dofferhof, Roosje Kemmink, Mathieu Decuyper, Sanya van der Kleij, Anjo de Jong, Wouter de Vries, Aniek Henken, Thijs Buijserd, Sep Bregman, Igor Vunderink, Thijs Vlonk, Ciska den Boer, Aniek Kroezen, Gijs Gommers, Arne van Eupen, Gertjan de Wit, Eerste Jaar Licht 2024, Midden Groep Vrouwen 2025, Friends from Delft, Rowing related friends, Not rowing related Friends, Family and Half-Siblings.

Bibliography

Boer, K., & Schils, C. M. G. J. (2011). *Ecologisch groenbeheer in de praktijk*.

Bouwman, M., Akhmetzyanov, L., Mohren, F., den Ouden, J., Sass-Klaassen, U., & Copini, P. (2025). Tree growth responses to severe droughts for assessment of forest growth potential under future climate. *Forest Ecology and Management*, *578*(November 2024), 122423. https://doi.org/10.1016/j.foreco.2024.122423

Brown, N., Inward, D. J. G., Jeger, M., & Denman, S. (2015). A review of Agrilus biguttatus in UK forests and its relationship with acute oak decline. *Forestry*, *88*(1), 53–63. https://doi.org/10.1093/forestry/cpu039

Bunn, A. G. (2008). A dendrochronology program library in R (dplR). *Dendrochronologia*, *26*(2), 115–124. https://doi.org/10.1016/j.dendro.2008.01.002

Buras, A., Rammig, A., & Zang, C. S. (2020). A novel approach for the identification of pointer years. *Dendrochronologia*, *63*(July), 125746. https://doi.org/10.1016/j.dendro.2020.125746

Caudullo, G., Welk, E., & San-Miguel-Ayanz, J. (2017). *Distribution map of pedunculate oak (Quercus robur)*. https://figshare.com/articles/dataset/Quercus_robur_chorology/5114080?file=13820090

Compendium voor de Leefomgeving. (2023a). *Jaar temperatuur Nederland*. https://www.clo.nl/indicatoren/nl022615-temperatuur-in-nederland-en-mondiaal-1907-2022

Compendium voor de Leefomgeving. (2023b). *Jaarlijkse hoeveelheid neerslag in Nederland, 1910-2022*. https://www.clo.nl/indicatoren/nl050809-jaarlijkse-hoeveelheid-neerslag-in-nederland-1910-2022

Denman, S., Kirk, S., & Webber, J. (2010). Managing acute oak decline. *Practice Note - Forestry Commission*, *15*, 6 pp. https://cdn.forestresearch.gov.uk/2022/02/managing_acute_oak_decline_fcpn015_3.pdf

Di Filippo, A., Alessandrini, A., Biondi, F., Blasi, S., Portoghesi, L., & Piovesan, G. (2010). Climate change and oak growth decline: Dendroecology and stand productivity of a Turkey oak (Quercus cerris L.) old stored coppice in Central Italy. *Annals of Forest Science*, *67*(7). https://doi.org/10.1051/forest/2010031

Eaton, E., Caudullo, G., Oliveira, S., & Rigo, D. de. (2015). Quercus robur and Quercus petraea in Europe: distribution, habitat, usage and threats. *Biosystems Diversity*, *23*(2), 160–163. https://doi.org/10.15421/011515

Ellenberg, H. (1988). *Vegetation Ecology of Central Europe*. https://books.google.nl/books?hl=nl&lr=&id=LQNxbuyPxawC&oi=fnd&pg=PR15&dq=ellenberg+1988&ots=ONvvyYh2e8&sig=HD9usi5icXj3abZZk2MutlSNd50#v=onepage&q=ellenberg 1988&f=false

Gagen, M., Matthews, N., Denman, S., Bridge, M., Peace, A., Pike, R., & Young, G. (2019). The tree ring growth histories of UK native oaks as a tool for investigating Chronic Oak Decline: An example from the Forest of Dean. *Dendrochronologia*, *55*(March), 50–59. https://doi.org/10.1016/j.dendro.2019.03.001

Gibbs, J. N., & Greig, B. J. W. (1997). Biotic and abiotic factors affecting the dying back of pedunculate oak Quercus robur L. *Forestry*, *70*(4), 403–406. https://doi.org/10.1093/forestry/70.4.399

Gosling, R. H., Jackson, R. W., Elliot, M., & Nichols, C. P. (2024). Oak declines: Reviewing the evidence for causes, management implications and research gaps. *Ecological Solutions and Evidence*, *5*(4), 1–18. https://doi.org/10.1002/2688-8319.12395

Heybroek, H. M. (1989). Cultuurhistorie van de eik. *Nederlands Bosbouwtijdschrift*, *61*(6), 159–164.

IStock. (2025). *Eikenblad*. https://www.istockphoto.com/nl/vector/eikenbladeren-en-eikels-tekening-gm1180394550-330677163

Jactel, H., Koricheva, J., & Castagneyrol, B. (2019). Responses of forest insect pests to climate change: not so simple. *Current Opinion in Insect Science*, *35*, 103–108. https://doi.org/10.1016/j.cois.2019.07.010

Jevšenak, J., & Levanič, T. (2015). Dendrochronological and wood-anatomical features of differently vital pedunculate oak (Quercus robur L.) stands and their response to climate. *Topola / Poplar*, *188*(195–196), 85–96. http://scindeks-clanci.ceon.rs/data/pdf/0563-9034/2015/0563-90341596085J.pdf

Klesse, S., & Bigler, C. (2025). Growth trends in basal area increments: The underlying problem, consequences for research and best practices. *Dendrochronologia*, *90*, 126296. https://doi.org/10.1016/j.dendro.2025.126296

KNMI. (2024). *De staat van ons klimaat 2023: warmste en natste jaar ooit gemeten*. https://www.knmi.nl/over-het-knmi/nieuws/de-staat-van-ons-klimaat-2023-warmste-en-natste-jaar-ooit-gemeten

KNMI. (2025a). *Hellmann-koudegetallen*. https://www.knmi.nl/nederland-nu/klimatologie/lijsten/hellmann

KNMI. (2025b). *Warmtegetallen*. https://www.knmi.nl/nederland-nu/klimatologie/lijsten/warmtegetallen

Krutovsky, K. V., Popova, A. A., Yakovlev, I. A., Yanbaev, Y. A., & Matveev, S. M. (2025). Response of Pedunculate Oak (Quercus robur L.) to Adverse Environmental Conditions in Genetic and Dendrochronological Studies. *Plants*, *14*(1), 1–39. https://doi.org/10.3390/plants14010109

Losseau, J., Jonard, M., & Vincke, C. (2020). Pedunculate oak decline in southern Belgium: A long-term process highlighting the complex interplay among drought, winter frost, biotic attacks, and masting. *Canadian Journal of Forest Research*, *50*(4), 380–389. https://doi.org/10.1139/cjfr-2019-0341

Lucassen, E., Aben, R., Smolders, A., Bobbink, R., van Diggelen, J., van Roosmalen, M., Boxman, D., van den Berg, L., & Roelofs, J. (2014). Bodemverzuring als aanjager van eikensterfte: gevolgen voorherstelmaatregelen. *Vakblad Natuur Bos Landschap*, *11*(103), 23–27. https://www.researchgate.net/publication/299848879_Bodemverzuring_als_aanjager_van_eikensterfte_gevolgen_voor_herstelmaatregelen?enrichId=rgreq-b9aede47c3e55a0d2fe53b36afb1b225-XXX&enrichSource=Y292ZXJQYWdlOzI5OTg0ODg3OTtBUzozNDgxOTIwNTE4NzU4NDBAMTQ2MDAyN

Lucassen, E. C. H. E. T., van den Berg, L. J. L., Smolders, A. J. P., Aben, R. C. H., Roelofs, J. G. M., & Bobbink, R. (2014). Bodemverzuring en achteruitgang zomereik. *Landschap*, *4*, 185–193. https://www.landschap.nl/wp-content/uploads/2014-4_185-193.pdf

Lucassen, E., Dr. L.J.L. van den Berg, Dr. A.J.P. Smolders, MSc. R.C.H. Aben, Prof. Dr. J.G.M. Roelofs, & Dr. R. Bobbink. (2014). Bodemverzuring en achteruitgang zomereik. In *Landschap* (Issue 4, pp. 185–193).

Macháčová, M., Nakládal, O., Samek, M., Baťa, D., Zumr, V., & Pešková, V. (2022). Oak Decline Caused by Biotic and Abiotic Factors in Central Europe: A Case Study from the Czech Republic. *Forests*, *13*(8). https://doi.org/10.3390/f13081223

Meijenfeldt, A. (2023). *Pedunculate oak decline in the Netherlands*. *1156802*, 0–31.

Moraal, L. (2003). insecten plagen op bomen en klimaatsverandering. *De Levende Natuur*. https://natuurtijdschriften.nl/pub/495418/DLN1040900933.pdf

Moraal, L. G. (1997). *Eikenprachtkever, Agrilus biguttatus, en eikensterfte: een literatuurstudie over aantastingen, levenswijze en verspreiding*. https://edepot.wur.nl/389507

Moraal, L. G., & Hilszczanski, J. (2000). The oak buprestid beetle, Agrilus biguttatus (F.) (Col., Buprestidae), a recent factor in oak decline in Europe. *Anzeiger Fur Schadlingskunde*, *73*(5), 134–138. https://doi.org/10.1007/BF02956447

Niemczyk, M., Karwański, M., & Grzybowska, U. (2017). Effect of environmental factors on occurrence of cockchafers (Melolontha spp.) in forest stands. *Baltic Forestry*, *23*(2), 334–341. https://www.researchgate.net/publication/317719403_Effect_of_environmental_factors_on_occurrence_of_cockchafers_Melolontha_spp_in_forest_stands?enrichId=rgreq-0e566a89aeab7ff4a82ec3ac5d3d1fc8-XXX&enrichSource=Y292ZXJQYWdlOzMxNzcxOTQwMztBUzo1OTIwNjE5MDAyNz

Oosterbaan, A. Bobbink, R. Decuyper, M. (2014). *Onderzoek naar de relatie van eikensterfte met droogte en bodemchemie*. https://www.researchgate.net/publication/283416877_Onderzoek_naar_de_relatie_van_eikensterfte_met_droogte_en_bodemchemie?enrichId=rgreq-4d2978ead67d3106f373b1a9ef8dde4b-XXX&enrichSource=Y292ZXJQYWdlOzI4MzQxNjg3NztBUzozMTQ0NTc1NjgyODQ2NzRAMTQ1MTk4MzkzNDYyN

Oosterbaan, A. (2014). Eikensterfte: ernst, oorzaken en beheer. *Vakblad Natuur Bos Landschap*, 22–25. https://ecopedia.s3.eu-central-1.amazonaws.com/pdfs/563.pdf

Oosterbaan, A. (2015). *Eikensterfte : een serieus en complex probleem*. 10–14. https://scispace.com/pdf/eikensterfte-een-serieus-en-complex-probleem-3530lugyvd.pdf

Oosterbaan, A., & Nabuurs, G. J. (1991). Relationships between oak decline and groundwater class in The Netherlands. *Plant and Soil*, *136*(1), 87–93. https://doi.org/10.1007/BF02465223

Rozas, V., & Sampedro, L. (2013). Soil chemical properties and dieback of Quercus robur in Atlantic wet forests after a weather extreme. *Plant and Soil*, *373*(1–2), 673–685. https://doi.org/10.1007/s11104-013-1835-5

Schelhaas, M. J., Teeuwen, S., Oldenburger, J., Beerkens, G., Velema, G., Kremers, J.,

Lerink, B., Paulo, M. J., Schoonderwoerd, H., Daamen, W., Dolstra, F., Lusink, M., Tongeren, K. Van, Scholten, T., & Voncken, F. (2022). Zevende Nederlandse Bosinventarisatie. *Wettelijke Onderzoekstaken Natuur & Milieu*, 127. https://www.np-utrechtseheuvelrug.nl/wp-content/uploads/2022/07/Nederlandse_bosinventarisatie.pdf

Schmull, M., & Thomas, F. M. (2000). Morphological and physiological reactions of young deciduous trees (quercus robur l., Q. Petraea [Matt.] Liebl., Fagus sylvatica l.) to waterlogging. *Plant and Soil*, *225*(1–2), 227–242. https://doi.org/10.1023/A:1026516027096

Skeffington, R. A., & Wilson, E. J. (1988). Excess nitrogen deposition: Issues for consideration. *Environmental Pollution*, *54*(3–4), 159–184. https://doi.org/10.1016/0269-7491(88)90110-8

Temperatuur in Nederland en mondiaal, 1907 - 2022. (2023). https://www.clo.nl/indicatoren/nl022615-temperatuur-in-nederland-en-mondiaal-1907-2022

Thomas, F. Meyer, G. Popp, M. (2004). Effects of defoliation on the frost hardiness and the concentrations of soluble sugars and cyclitols in the bark tissue of pedunculate oak (Quercus robur L.). *Annals of Forest Science*, *64*(January), 219–228. https://doi.org/10.1051/forest:2004039

Thomas, F. M. (2008). Recent advances in cause-effect research on oak decline in Europe. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources*, *3*(037). https://doi.org/10.1079/PAVSNNR20083037

Thomas, F. M., & Blank, R. (1996). Defoliation on the Frost Hardiness of Bark Tissue. *Annales Des Sciences Forestieres*, *53*, 395–406. https://doi.org/https://doi.org/10.1051/forest:19960222

Thomas, F. M., Blank, R., & Hartmann, G. (2002). Abiotic and biotic factors and their interactions as causes of oak decline in Central Europe. *Forest Pathology*, *32*(4–5), 277–307. https://doi.org/10.1046/j.1439-0329.2002.00291.x

Turok, J., Kremer, A., & de Vries, S. (1997). *First EUFORGEN Meeting on Social Broadleaves*. https://www.euforgen.org/publications/publication/social-broadleaves-network-report-of-the-first-meeting

van den Burg, A., Dees, A., Huigens, T., Bijlsma, R.-J., & de Waal, R. (2014). *Voedselkwaliteit en biodiversiteit in bossen van de hoge zandgronden*. *Rapport nr. 2014/OBN186-DZ*, 1–128. https://edepot.wur.nl/295522

van der Maaten-Theunissen, M., van der Maaten, E., & Bouriaud, O. (2015). PointRes: An R package to analyze pointer years and components of resilience. *Dendrochronologia*, *35*, 34–38. https://doi.org/10.1016/j.dendro.2015.05.006

Verdonschot, R., Penning, E., Berends, K., Schoelynck, J., Rietsema, R., & Verdonschot, P. (2021). *Kennisnetwerk OBN*. https://edepot.wur.nl/506776

Visser, H. (2005). The significance of climate change in the Netherlands: An analysis of historical and future trends (1901-2020) in weather conditions, weather extremes and temperature-related impacts. *RIVM Report 550002007/2005*, 155. http://www.mnp.nl/en/publications/2005/The_significance_of_climate_change_in_the_Netherlands.html

Weijters, M. Bobbink, R. (2000). *Vijf decennia te veel stikstof : de effecten op heide en bos*.

41(2). https://b-ware.eu/sites/default/files/publicaties/Landschap 2024-2-Vijf decennia te veel stikstof 87-96.pdf

Weijters, M., Bobbink, R., & Siepel, H. (2020). *Selectie en uitzetten steenmeeltrails voor herstel van Oude Eikenbossen op arme zandgronden (H9190)*. *Rapportnum*, 1–48. https://www.ru.nl/onderzoek/onderzoeksprojecten/herstel-van-oude-eikenbossen-met-steenmeel

WSL, Switzerland. (n.d.). Retrieved February 24, 2025, from https://www.wsl.ch/en/services-produkte/microtomes/

Zang, C., & Biondi, F. (2015). Treeclim: An R package for the numerical calibration of proxy-climate relationships. *Ecography*, *38*(4), 431–436. https://doi.org/10.1111/ecog.01335

Appendix 1.0 – Motivation Rock dust Trial

In Northwestern Europe including the Netherlands excessive deposition of nitrogen compounds (NOX, NH4) from agriculture and industry has a complex effect on the environment. The additional nitrogen input leads to an increase of nitrogen availability and increased mineralization resulting in eutrophication. Deposited ammonium (NH4) breaks down in nitrate and releases two protons per N-molecule, resulting in increased acidification. The acidification causes a runoff of base cations like Ca, Mg and K (Verdonschot et al., 2021). The deficiency of base cations causes lower macro/micro nutrient concentrations in leaves, and increase of nitrogen lead to a disbalance between N and other ions. (Lucassen et al., 2014; Thomas et al., 2002; Weijters et al., 2020). On acidified soils pedunculate oaks has difficulties developing sufficient concentrations of allelochemicals, to defend itself against pest insect (Verdonschot et al., 2021). Secondly, acidification also causes the impairment of soil mycorrhization (Thomas et al., 2002), which usually take care of the P absorption (Lucassen et al., 2014). Acidification can also lead to toxic nitrate levels, leading to root damage (Verdonschot et al., 2021). Finally, nitrogen also increases the trees susceptibility to frost damage by decreasing their frost hardiness. A experiment done by (Skeffington & Wilson, 1988) shows that there is a significant increase of electrolytes leakage in pedunculate and sessile oaks from forest with high nitrogen deposition at -10 degrees Celsius in comparison to forest with low nitrogen deposition. The consequence of high nitrogen availability is the deficient assimilation of proteins and amino acids in leaves, this is the main reason populations of butterfly caterpillars have a poor development on pedunculate oaks. This poor development has a snowball effect on the whole trophic system (Verdonschot et al., 2021). To mitigate the effects of nitrogen the province of Gelderland has ordered an experiment to improve the conditions of forest by rock dust application.

Appendix 2.0 - Additional Site-specific information

Location 5 - Eikenheg

Location Eikenheg is an old growth oak forest, with little to no undergrowth see figure 22 and 23 for overview and elevation map and see table 5 for soil chemical characteristics. In certain area's wild boar completely uprooted the forest floor. By the uprooting, there was no clear transition from the organic material layer to the soil. However, mostly there was a layer of organic material of 10 cm thick. Plot EH1 transitions into coniferous forest, here the trees were 50/50, oak/conifer. While sampling for the third soil-samples, they uncovered much agricultural plastic. Therefore there is no soil-sample taken for pole PQ EH1-3 (Weijters et al., 2020).

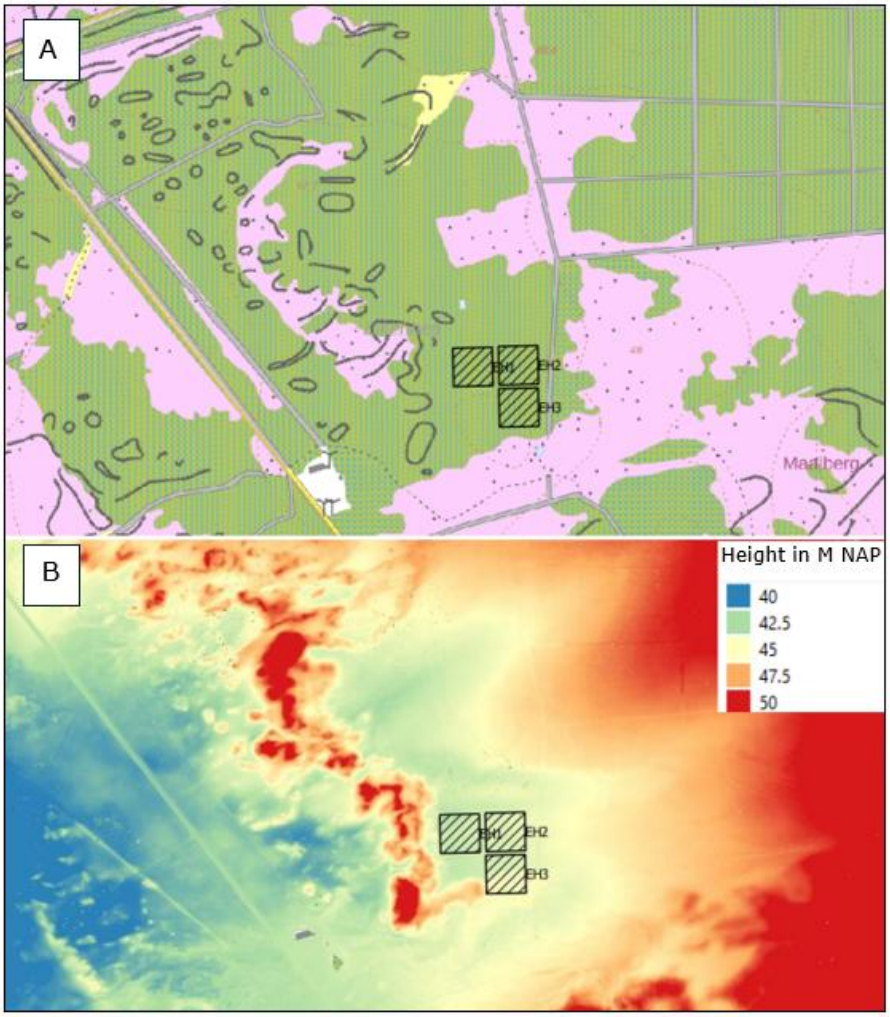

Figure 22: Location 5, Black square with slashed striped are the coded plots. A: overview of vegetations type, pink= heathland, green = forest, yellow = drift sands, lines represent roads. B: altitude map, with red as high and blue as low. Source: (Weijters et al., 2020)

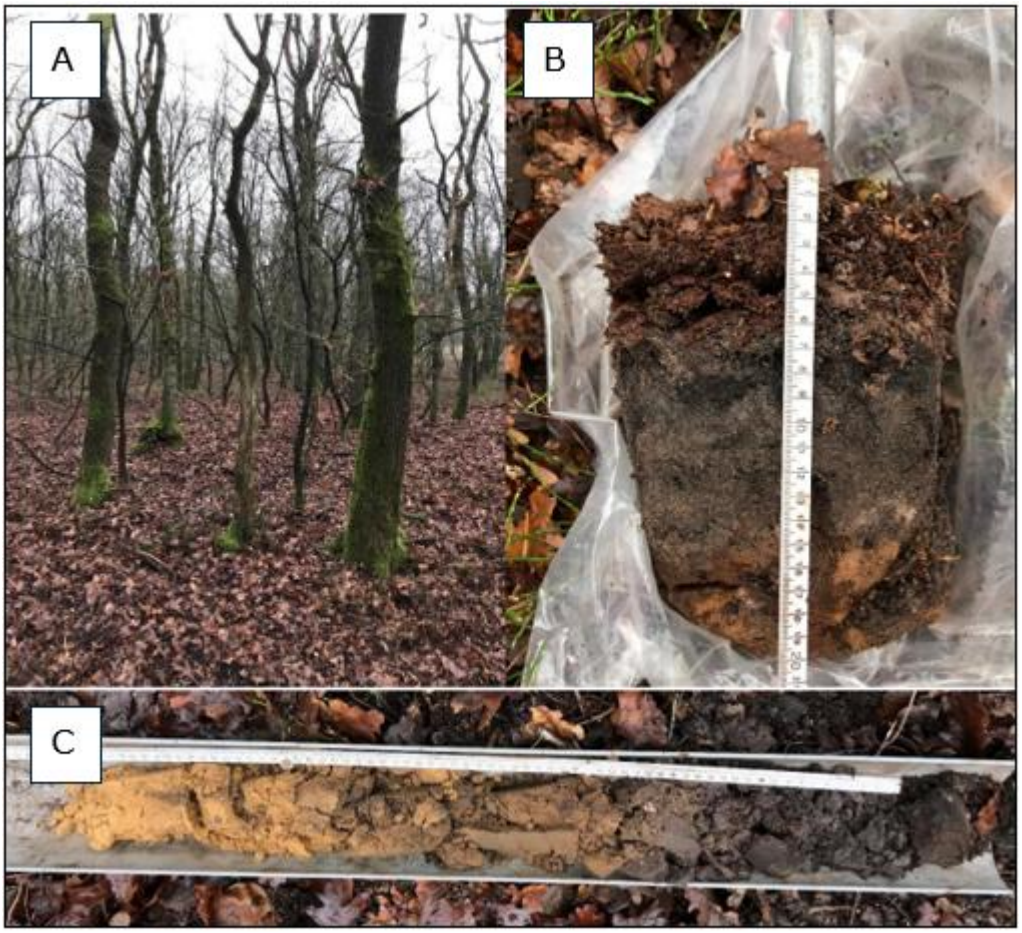

Figure 23: Overview of forest and soil sample. A: Pedunculate Oak forest, picture taken in winter. B: soil sample top 20cm, top 6 cm organic layer, marginal transition to sandy soil. C: Soil sample total of 80cm. On the right side is the surface, the distinct black color is leakage of organic matter. There is a smooth gradual transition from black to gray to brown and finally bare sand. Source: (Weijters et al., 2020)

Table 5: Soil chemical characteristics for location 5. per plot there are 4 samples taken form 4 different depts: OH = organic litter layer, and subsequently 0-10cm, 10-20 cm, 20-40cm dept. Source: (Weijters et al., 2020)

nr	locatie	diepte	Organische stof	pH-NaCl	Al	Ca	Fe	K	Mg	Mn	P	Zn	NO3	NH4	Al/Ca
			(%)		µmol/kg	µmol/kg	µmol/kg	µmol/kg	µmol/kg	µmol/kg	µmol/kg	µmol/kg	µmol/kg	µmol/kg	mol/mol
5	EH 1	OH	16,8	2,78	1501	7094	38	1166	2874	1389	49	32	361	248	0,2
	EH 1	0-10	5,0	2,84	2264	1757	38	471	592	247	13	6	251	86	1,3
	EH 1	10-20	3,6	3,54	2224	415	23	425	167	60	2	6	116	51	5,4
	EH 1	20-40	2,2	3,88	942	223	8	344	90	31	1	5	70	40	4,2
	EH 2	OH	34,0	2,74	1417	11507	40	2854	7621	1728	50	102	486	1711	0,1
	EH 2	0-10	6,2	2,77	2339	863	28	589	516	22	5	22	186	152	2,7
	EH 2	10-20	3,6	3,31	2343	422	31	335	187	34	1	6	136	152	5,6
	EH 2	20-40	2,1	3,92	972	161	10	255	87	14	1	3	162	110	6,0
	EH 3	OH	27,4	2,68	796	11134	20	3216	5896	943	80	85	1254	1316	0,1
	EH 3	0-10	4,3	2,98	1540	798	21	460	369	44	9	5	177	140	1,9
	EH 3	10-20	2,5	3,48	1578	382	32	302	212	28	1	3	105	94	4,1
	EH 3	20-40	1,6	2,68	763	381	15	846	175	31	1	3	103	53	2,0

nr	locatie	diepte	Strontium BV	CEC	Destructie Al	Ca	Fe	K	Mg	P	CN N	C	C/N
			%	meq/kg	mmol/kg	mmol/kg	mmol/kg	mmol/kg	mmol/kg	mmol/kg	mg/g	mg/g	g/g
5	EH 1	OH	24,1	78	35,1	7,6	30,4	2,3	4,1	4,8	4	76,9	19,2
	EH 1	0-10	19,7	39	47,1	3,5	39,1	2,5	4,6	2,7	1	23,9	23,9
	EH 1	10-20	9,8	22	75,7	2,7	55,0	2,1	4,9	2,2	0,8	19,8	24,8
	EH 1	20-40	18,2	10	100,8	2,2	52,8	1,8	5,7	1,9	0,4	11	27,5
	EH 2	OH	33,9	131	42,4	14,9	34,2	3,9	7,6	7,3	7,4	150,4	20,3
	EH 2	0-10	9,2	43	42,1	2,3	37,0	2,0	2,8	2,2	1,2	34,9	29,1
	EH 2	10-20	7,9	27	59,3	1,9	48,6	1,6	2,7	2,0	0,6	18,1	30,2
	EH 2	20-40	11,8	12	100,0	2,4	52,6	1,7	4,6	2,0	0,4	11	27,5
	EH 3	OH	31,9	141	31,9	16,2	23,2	4,2	7,2	7,6	8	149,3	18,7
	EH 3	0-10	12,6	34	36,0	2,6	27,0	2,1	2,9	2,3	8,3	151,2	18,2
	EH 3	10-20	11,9	21	47,4	2,4	34,9	1,9	4,2	1,2	1	26	26,0
	EH 3	20-40	18,3	12	69,3	2,6	33,4	1,8	6,3	1,1	0,4	12,5	31,3

Location 6 - Heidenseberg

Heidenseberg is an old growth Pedunculate oak forest. Here is searched for as much as blueberry undergrowth see figure 24 for overview and elevation map, see table 6 for soil chemical characteristics. The location is rich in relief and partially uprooted by wild boar. By the uprooting, the upper soil structure varied al lot between places. The thickness of the organic layer varied from 0-10 cm. The deeper soil layers contained brown/grey sands with locally much variation in soil structure. On location HB2-3 they found a black layer 70cm below the surface. On location HB3-3 just yellow sand was found in the deeper soil layer. A dark layer was also found in the deeper soil layers at locations HB1-2 and HB1-1 see figure 25.

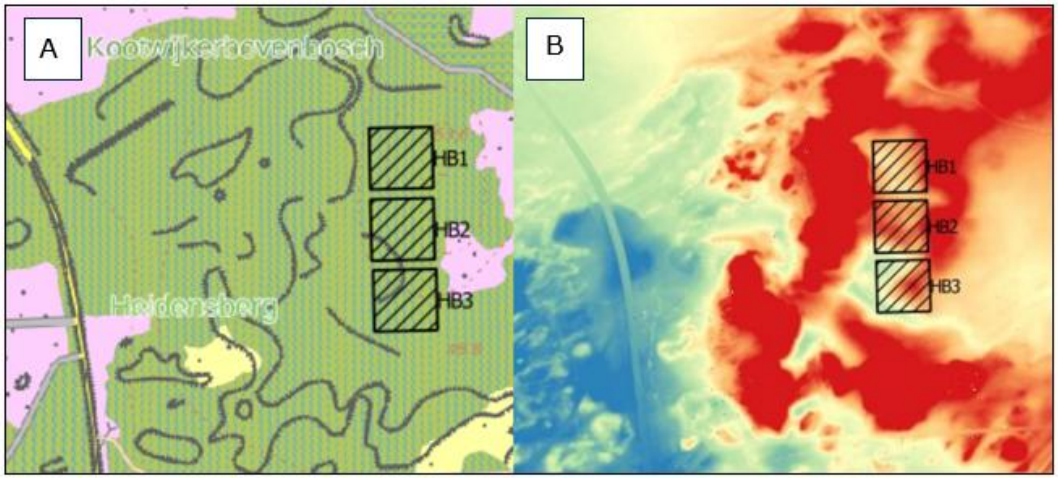

Figure 24: Location 6, Black square with slashed stripes are the coded plots. A: overview of vegetations type, pink= heathland, green = forest, yellow = drift sands, straight through lines represents roads. B: altitude map, with red as high and blue as low. Source: (Weijters et al., 2020)

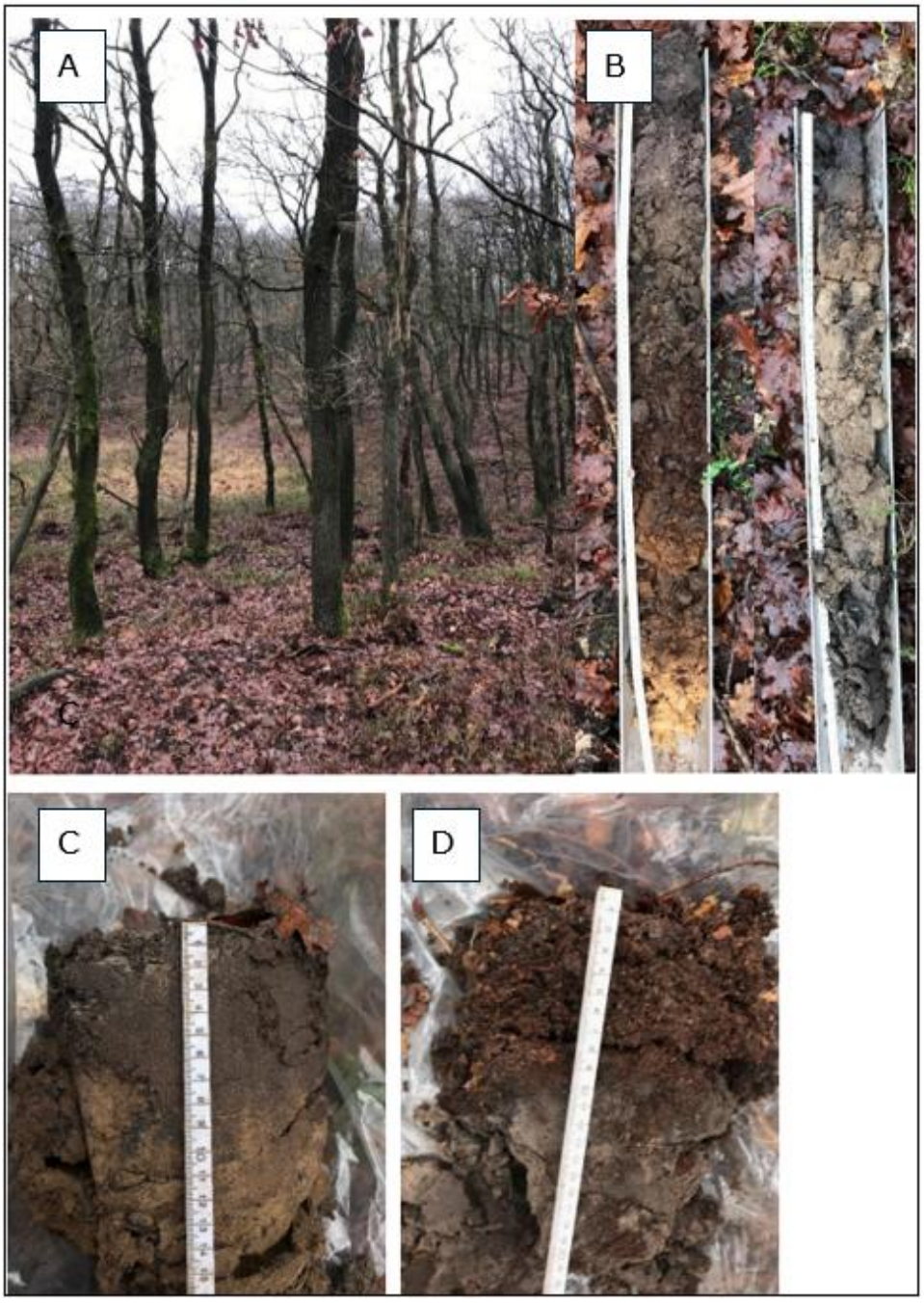

Figure 25: Overview of forest and soil sample. A: Pedunculate Oak forest with blueberry undergrowth, picture taken in winter. B: 2 distinct soil samples 80-100cm deep from top to bottom. Samples show very different soil characteristic within the plot. The left sample (HB3-3) shows a black/gray layer with smooth transition to brown and finally smooth transition to bright yellow sand. The right soil sample (HB1-2) starts dark gray, transitions abrupt to pale white/gray sand, and finally a smooth transition to a second organic black layer starting on 70cm dept. C: Soil sample (HB3-3) of top 15cm, with no litter layer. D: soil sample (HB2-2) of top 20cm with thick litter layer of 8cm. Source: (Weijters et al., 2020)

Table 6: Soil chemical characteristics for location 6. Per plot there are 4 samples taken from 4 different depts: OH = organic litter layer, and subsequently 0-10cm, 10-20 cm, 20-40cm dept.

				Zout (0,2 NaCl)											
nr	**locatie**	**diepte**	**Organische stof**	**pH-NaCl**	**Al**	**Ca**	**Fe**	**K**	**Mg**	**Mn**	**P**	**Zn**	**NO3**	**NH4**	**Al/Ca**
			(%)		µmol/kg	µmol/kg	µmol/kg	µmol/kg	µmol/kg	µmol/kg	µmol/kg	µmol/kg	µmol/kg	µmol/kg	mol/mol
6	HB 1	OH	30,1	2,85	325	13647	29	3218	8432	1491	130	70	1239	1858	0,0
	HB 1	0-10	7,6	2,81	1610	1502	20	623	735	48	9	15	227	61	1,1
	HB 1	10-20	2,8	3,58	1788	419	21	312	194	22	1	4	129	78	4,3
	HB 1	20-40	3,1	3,81	1348	302	10	313	136	14	1	4	109	53	4,5
	HB 2	OH	48,8	2,74	340	18344	29	4089	10570	1754	213	114	1811	2628	0,0
	HB 2	0-10	5,7	2,87	1828	1566	34	423	717	86	5	7	186	133	1,2
	HB 2	10-20	4,8	3,42	2609	782	34	356	363	43	1	7	144	108	3,3
	HB 2	20-40	4,9	3,68	1680	528	14	314	244	35	1	5	143	73	3,2
	HB 3	OH	13,7	2,81	1179	5528	26	1161	2898	371	31	34	642	297	0,2
	HB 3	0-10	4,5	3,11	2142	603	43	415	366	27	3	7	193	115	3,6
	HB 3	10-20	4,1	3,72	2391	354	25	341	206	18	1	5	197	90	6,8
	HB 3	20-40	3,5	3,90	1501	232	10	260	125	10	1	4	192	51	6,5

			Strontium		Destructie						CN		
nr	**locatie**	**diepte**	**BV**	**CEC**	**Al**	**Ca**	**Fe**	**K**	**Mg**	**P**	**N**	**C**	**C/N**
			%	meq/kg	mmol/kg	mmol/kg	mmol/kg	mmol/kg	mmol/kg	mmol/kg	mg/g	mg/g	g/g
6	HB 1	OH	42,6	141	31,6	18,0	22,7	4,1	8,7	7,1	8,6	158,9	18,5
	HB 1	0-10	25,3	48	39,2	3,9	25,7	2,6	3,8	2,5	1,8	35,7	19,8
	HB 1	10-20	9,4	22	63,7	3,1	34,5	2,4	6,2	1,4	0,6	15,8	26,3
	HB 1	20-40	9,7	17	69,7	2,3	28,1	1,8	5,0	1,4	0,5	15,7	31,4
	HB 2	OH	42,3	186	30,7	31,1	22,4	5,1	11,3	9,4	13,4	252,9	18,9
	HB 2	0-10	13,3	40	42,5	3,8	31,8	2,3	4,1	2,1	1,2	27,5	22,9
	HB 2	10-20	10,0	36	77,1	3,4	41,4	2,2	5,5	2,2	1	28,1	28,1
	HB 2	20-40	16,8	24	65,7	1,9	21,2	1,2	2,2	1,3	0,7	27,2	38,9
	HB 3	OH	25,6	75	38,2	7,7	28,2	2,8	4,9	3,8	3,8	75,9	20,0
	HB 3	0-10	9,4	34	45,6	2,3	35,7	1,9	3,6	1,7	1	25,2	25,2
	HB 3	10-20	8,7	26	76,3	2,1	40,8	1,9	3,6	1,5	0,8	24,1	30,1
	HB 3	20-40	13,2	18	86,5	2,2	33,7	1,3	2,4	1,5	0,6	20,3	33,8